

Detection of Erythromycin-Resistant Determinants by PCR

JOYCE SUTCLIFFE,* THORSTEN GREBE, AMELIA TAIT-KAMRADT, AND LILLIAN WONDRACK

Department of Infectious Diseases, Central Research Division, Pfizer, Inc., Groton, Connecticut 06340

Received 24 June 1996/Returned for modification 22 August 1996/Accepted 12 September 1996

Erythromycin resistance determinants include Erm methylases, efflux pumps, and inactivating enzymes. To distinguish the different mechanisms of resistance in clinical isolates, PCR primers were designed so that amplification of the partial gene products could be detected in multiplex PCRs. This methodology enables the direct sequencing of amplified PCR products that can be used to compare resistance determinants in clinical strains. Further, this methodology could be useful in surveillance studies of erythromycin-resistant determinants.

Three different mechanisms of erythromycin resistance have been described (26–28, 54). Target modification is mediated by an rRNA *erm* methylase that alters a site in 23S rRNA common to the binding of macrolides, lincosamides, and streptogramin B antibiotics (26, 28, 54). Enzymes (*EreA* and *EreB*) that hydrolyze the lactone ring of the macrocyclic nucleus (2–4, 7, 38, 40, 41) and phosphotransferases (type I [*mphA*] [23, 37, 39] and type II [24]) that inactivate macrolides by introducing a phosphate on the 2'-hydroxyl group of the amino sugar have been reported in members of the family *Enterobacteriaceae* and, recently, in *Staphylococcus aureus* (56). The presence of multicomponent macrolide efflux pumps in staphylococci (*msrA*, *msrB*) (15, 21, 22, 31, 45, 46) and *Neisseria gonorrhoeae* (*mtr*) (17, 42) as well as an efflux system in streptococci (*mefA*, *mefE*) (12, 51, 52) has also been documented.

A set of degenerate primers designed to detect the *erm* classes predominantly found in pathogenic bacteria has been reported (5). However, primers designed to detect other erythromycin resistance determinants have not been described, despite the growing citations of the prevalence of these alternate

resistance mechanisms (8, 14, 21, 22, 49, 51, 55). To aid in surveillance of erythromycin resistance determinants, we have developed PCR primers that detect the presence of macrolide efflux (*msrA/msrB* or *mefA/E*) and drug inactivation (*ereA*, *ereB*, *mphA*). Further, we have also designed primers to distinguish the *ermA*, *ermB*, and *ermC* classes found in pathogenic bacteria.

MATERIALS AND METHODS

Strains. Table 1 lists the origins and descriptions of the reference strains. Table 2 describes the clinical strains and their sources.

Chemicals. Brain heart infusion was obtained from Difco Laboratories; brain heart infusion and blood agar plates were purchased from Remel Microbiology Products (Lenexa, Kans.). PCR buffers and DNA polymerase were supplied by Perkin-Elmer (Danbury, Conn.), and all DNA primers were purchased from GenoSys Biotechnologies (The Woodlands, Tex.).

Design of oligonucleotide primers for *erm* determinants. Using the multiple sequence alignment program available in BLAST, the rRNA methylases were aligned to reveal the presence of regions with invariant amino acids per *erm* class. Regions of seven to eight amino acids present in all deduced sequences of cloned *erm* genes by class were chosen and evaluated for stem-loop structures and specificity for the *erm* class determinant using programs available in the Genetics Computer Group, Inc. (Madison, Wis.), sequence analysis software programs.

The macrolide efflux determinants *msrA* (46, 47) and *msrB* (32) from *Staphylococcus epidermidis* and *Staphylococcus xylosum*, respectively, were compared with each other and with other efflux proteins using the TFASTA program of the Genetics Computer Group. Primers specific for the second ATP-binding cassette region of *msrA* and the single ATP-binding cassette region of *msrB* and distinguishable from *vga*, a streptogramin A putative efflux determinant (1, 15), were designed.

Primers for *ereA* (41), *ereB* (3), and *mphA* (23, 37) were designed from published sequences to provide specific PCR products of 420, 546, and 837 bp, respectively. For these experiments, the *ereA* primers were 5'-AACACCCTGAACCAAGGGACG-3' and 5'-CTTCACATCCGGATTGCTCGA-3'; the *ereB* primers were 5'-AGAAATGGAGGTTTCATACTTACCA-3' and 5'-CATAAATCATCACCAATGGCA-3'; the *mphA* primers were 5'-AACTGTACGC ACTTGC-3' and 5'-GGTACTCTTCGTTACC-3'. Primers for the *mefA/mefE* genes in *Streptococcus pyogenes* and *Streptococcus pneumoniae* were designed

TABLE 1. Origin and description of reference strains

Organism	Gene	Location of gene(s)	Reference or source
<i>S. aureus</i> RN1389	<i>ermA</i>	Tn554 in the chromosome	34
<i>S. pyogenes</i> AC1 (pAC1)	<i>ermB</i>	Plasmid pAC1	13
<i>S. pyogenes</i> 02C1064	<i>mefA^a</i>	Unknown	12
<i>E. faecalis</i> JH2-2 (pJH1)	<i>ermB</i>	Plasmid pJH1	20
<i>S. aureus</i> RN4220 (pE194)	<i>ermC</i>	Plasmid pE194	19
<i>S. epidermidis</i> S1187	<i>msrA</i>	Large plasmid	46
<i>S. pneumoniae</i> 02J1175	<i>mefE^b</i>	Unknown	52
<i>E. coli</i> BM694 (pAT63)	<i>ereA</i>	pBR322 plasmid with cloned insert	41
<i>E. coli</i> BM694 (pAT72)	<i>ereB</i>	pUC8 plasmid with cloned insert	3
<i>E. coli</i> BM2506	<i>mph</i> type II	Probably plasmid	24
<i>E. coli</i> BM2570	<i>ereB</i> , <i>ermBC</i>	Plasmid pIP1527	4
<i>S. aureus</i> RN450 (pIP524)	<i>vga</i>	Plasmid pIP524	15
<i>E. coli</i> L441D	<i>mphA</i>	Unknown	37

^a *mefA*, macrolide efflux in *S. pyogenes*.

^b *mefE*, macrolide efflux in *S. pneumoniae*.

* Corresponding author. Mailing address: Department of Infectious Diseases, Central Research Division, Pfizer, Inc., Eastern Point Road, Groton, CT 06340. Phone: (860) 441-4693. Fax: (860) 441-6159. Electronic mail address: Joyce_A_Sutcliffe@groton.pfizer.com.

TABLE 2. Clinical strains and their sources

Organism	Source or reference	Original identification no.	Yr isolated
<i>S. epidermidis</i> 01B1034	Jenssen (25)	226A	1985
<i>S. aureus</i> 01A1018	Massachusetts	68933	1989
<i>E. faecalis</i> 03A1069	Missouri (CDC) ^a	HIP2025	1994
<i>S. pyogenes</i> 02C1076	Ireland	DC680	1994
<i>S. pyogenes</i> 02C1086	Indiana	V985100	1994
<i>S. pneumoniae</i> 02J1126	California	M28095	1994
<i>S. pneumoniae</i> 02J1092	Texas (CDC)	2033228	1994

^a CDC, Centers for Disease Control and Prevention, Atlanta, Ga.

	Primer I	Primer II
<i>ermA</i>	NH ₂ --14-- SER LYS LYS HIS VAL LYS GLU ----- 201 ----- 5'-- TCT AAA AAG CAT GTA AAA GAA → 3'	THR ASN ILE ASN LYS LEU SER LYS--14--COOH 3'← TGA TTA TAA TTA TTT GAT AGC TTC-- 5'
	PREDICTED PCR PRODUCT: 645 BP	
<i>ermB</i>	NH ₂ --14-- GLU LYS VAL LEU ASN GLN ILE ----- 202 ----- 5'-- GAA AAG GTA CTC AAC CAA ATA → 3'	VAL ASN ASN LEU SER THR VAL THR--18--COOH 3'← CAT TTG TTA AAT TCA TGG CAA TGA -- 5'
	PREDICTED PCR PRODUCT: 639 BP	
<i>ermC</i>	NH ₂ --14-- SER LYS HIS ASN ILE ASP LYS ----- 200 ----- 5'-- TCA AAA CAT AAT ATA GAT AAA → 3'	ILE ASP ASP LEU ASN ASN ILE SER--16--COOH 3'← TAA CTG CTA AAT TTG TTA TAA TCG -- 5'
	PREDICTED PCR PRODUCT: 642 BP	

FIG. 1. Sequences and primers to detect *ermA*, *ermB*, and *ermC*. The corresponding codons and nucleotide sequences of oligonucleotide primers for *ermA*, *ermB*, and *ermC* are shown. The numbers of amino acids between the different primer regions and the amino and carboxy termini are indicated for each primer set.

after comparison of the two sequences (12, 52); the primers were 5'-AGTATC ATTAATCACTAGTGC-3' and 5'-TTCTTCTGGTACTAAAAGTGG-3'.

Amplification protocol. Genomic DNA was isolated from *Escherichia coli* strains as described in reference 6. DNA recovery from the other species required modifications (51) to ensure adequate cell breakage.

The PCR mix was as recommended by Perkin-Elmer, with a magnesium concentration of 2 mM being preferred for the *ermA/ermB/ermC/msr* primer set (primer mix I) and 4 mM for the *ereA/ereB/mphA/mef* primer set (primer mix II). When the PCRs were done separately for each erythromycin-resistant determinant, 4 mM magnesium was used for the *ermA*, *msr*, *ereA*, *ereB*, *mphA*, and *mef* primer sets and 2 mM was used for the *ermB*, *ermC*, and consensus *erm* primer sets. PCR conditions were as described in reference 51; electrophoresis on 1% agarose gels in 40 mM Tris acetate-2 mM EDTA buffer was used to distinguish PCR products. The size of each PCR product was estimated using standard molecular weight markers (1-kb DNA ladder from Gibco BRL, Gaithersburg, Md.).

RESULTS

Amplification of *erm* and *msr* genes. Oligonucleotide pairs were designed to hybridize to either *ermA*, *ermB* (including *ermAM* and *ermBP*), or *ermC* sequences from pathogenic species. By comparing published sequences of *erm* genes from different pathogenic species and strains, a minimum of degeneracy was necessary in the design of the *erm* specific primers, allowing for annealing temperatures to be high. Figure 1 details the respective amino acids and nucleotide codons present in the different *erm* classes: *ermA*, *ermB*, and *ermC*. Note that only one deduced sequence of *ermA* was available for use (34), while seven deduced sequences were used for *ermB* (9, 11, 16, 18, 44, 50, 53), and five sequences were evaluated for *ermC* (10, 19, 25, 33, 43).

Because the expected PCR product from any of the *erm* primers (~640 bp) (Fig. 1) can be distinguished from the expected PCR product from *msrA/msrB* primers (~400 bp) (Fig. 2), PCR using the four primer sets was performed simultaneously on genomic DNA samples from each of the reference strains (Table 1). The reference strains contain either a single copy (*ermA*), multiple copies (*ermB*, *ermC*, *msrA*, *ereA*, *ereB*, or *vga*), or an unknown number of copies (*mphA*, *mefA*, *mefE*) of the specified antibiotic-resistant determinant. If a strain was shown to contain an *erm* gene, it was subjected to a secondary assay with individual primer sets to resolve the determinant as *ermA*, *ermB*, or *ermC*. Because of the specificity of

the primers and the reaction conditions, nonspecific bands were rarely noted with any species or strain tested. Another measure of integrity of the reaction mix and primer sets is inherent in the DNA sample from *S. aureus* RN1389, a strain that contains a single chromosomal copy of *ermA*. Each of the reference strains gave the expected results: *ermC* was found in *S. aureus* RN4220 (pE194), and *ermB* was detected in *S. pyogenes* AC1 (pAC1), *Enterococcus faecalis* JH2-2 (pJH1), and *E. coli* BM2570 (Fig. 3) (secondary assay data not shown).

The *msrA/msrB* primer set produced a distinguishable PCR product with *S. epidermidis* S1187, the reference strain for *msrA*, without producing a false positive with *S. aureus* RN450 (pIP524), a strain that carries a plasmid encoding *vga*, a putative efflux protein for streptogramin A closely related to *msrA/msrB* (Fig. 2). The *vga* gene sequence (1) differed by seven nucleotides (and two amino acids) within the E1 primer and by seven nucleotides (and two amino acids) within the E2 primer from *msrA/B* (Fig. 2).

Amplification of *ereA*, *ereB*, *mphA*, and *mef* determinants. *EreA* and *EreB* are esterases found in enteric strains highly resistant to erythromycin (2-4, 7, 38, 40, 41). Two different types of macrolide phosphotransferases have been distinguished based on enzymatic characterization (24, 39). However, the structural determinant for only type I, *mphA* (37) or *mphK* (23), has been determined. Recently, a macrolide efflux pump was described in *S. pyogenes* (12) and *S. pneumoniae* (51, 52). The pump, called *mefA* in *S. pyogenes* and *mefE* in *S. pneumoniae*, appears to belong to the major facilitator family (29, 36, 52) as it requires an active proton motive force (12, 51, 52). The two genes are ~90% identical (12, 52), and this form of macrolide resistance is prominent in recent clinical isolates (51).

PCRs using the primer sets designed for *ereA*, *ereB*, *mphA*, and *mef* could be performed with a mix containing the four primer sets. The different product sizes (420 bp for *ereA*, 546 bp for *ereB*, 837 bp for *mphA*, and 348 bp for *mefA/E*) are easily distinguishable on a 1% agarose gel. Figure 3 shows that when primer mix II was used to amplify DNA from strains with defined erythromycin-resistant determinants, an *ereA* product was seen with *E. coli* BM694 (pAT63); an *ereB* product was

	Primer I	Primer II
<i>MsrA/B</i>	NH ₂ --331-- ALA ASN GLY VAL GLY LYS THR THR ----- 119 ----- 5'-- GCA AAT GGT GTA GGT AAG ACA ACT → 3'	ILE LEU PHE THR SER HIS ASP --- 23 -- COOH 3'← TAA AAC AAA TGT AGT GTA CTA --- 5'
	PREDICTED PCR PRODUCT: 399 BP	
<i>Vga</i>	NH ₂ --19-- SER ASN GLY THR GLY LYS THR THR ----- 119 ----- 5'-- TCT AAT GGT ACA GGA AAG ACA ACG → 3'	ILE ILE PHE VAL SER HIS ASP --- 23 -- COOH 3'← TAT TAG AAA CAT AGA GTG CTA -- 5'
	PREDICTED PCR PRODUCT: 399 BP	

FIG. 2. Sequences and primers to detect *msrA/msrB* from *vga*. The corresponding codons and nucleotide sequence of oligonucleotide primers for *msrA/msrB* and *vga* are shown. The numbers of amino acids between the different primer regions and the amino and carboxy termini are indicated for each primer set.

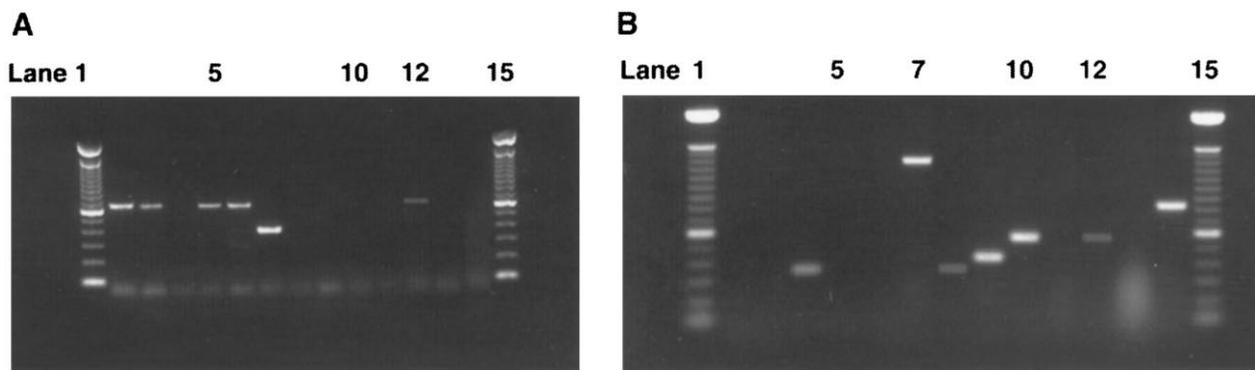


FIG. 3. PCR analysis of erythromycin-resistant determinants with reference strains. (A) PCR products observed using primer mix I (*ermA*, *ermB*, *ermC*, *msrA/msrB*); (B) PCR products observed using primer mix II (*ereA*, *ereB*, *mphA*, *mef*). Source of DNA for each lane: lanes 1 and 15, 1-kb DNA ladder; lane 2, DNA from *S. aureus* RN1389 (*ermA*); lane 3, *S. pyogenes* AC1 (pAC1) (*ermB*); lane 4, *S. pyogenes* 02C1064 (*mefA*); lane 5, *E. faecalis* JH2-2 (pJH1) (*ermB*); lane 6, *S. aureus* RN4220 (pE194) (*ermC*); lane 7, *S. epidermidis* S1187 (*msrA*); lane 8, *S. pneumoniae* O2J1175 (*mefE*); lane 9, *E. coli* BM694 (pAT63) (*ereA*); lane 10, *E. coli* BM694 (pAT72) (*ereB*); lane 11, *E. coli* BM2506 (*mph* type II); lane 12, *E. coli* BM2570 (*ereB*, *ermBC*); lane 13, *S. aureus* RN450 (pI524) (*vga*); lane 14, *E. coli* L441D (*mphA*). See Table 1 for origin of reference strains.

detected with *E. coli* BM694 (pAT72) and *E. coli* BM2570; an *mphA* product was observed with *E. coli* L441D and, notably, not with *E. coli* BM2506 (contains type II macrolide-2'-phosphotransferase); and an *mefA/E* product was seen with *S. pyogenes* 02C1064 and *S. pneumoniae* O2J1175. Interestingly, we observed a 1.2-kb product with DNA from *S. epidermidis* S1187, the reference strain for *msrA* (46). When the PCRs were primed separately, the product was found to be specific to the *mphA* primers (data not shown). This result supports our observation that this strain inactivates erythromycin (57) as well as effluxes macrolides (46). No products were seen in strains known to contain only Erm methylases.

Detection of erythromycin-resistant genes in clinical gram-positive isolates. The primer sets described in this report were used to amplify genomic DNA from representative isolates of erythromycin-resistant *S. epidermidis*, *S. aureus*, *E. faecalis*, *S. pyogenes*, and *S. pneumoniae* (Fig. 4). Erythromycin resistance in the *S. epidermidis* clinical strain O1B1034 appears to be both efflux mediated and due to inactivation as evidenced by our previous results (57) and confirmed in the PCR analysis. An

msrA-specific PCR product (~400 bp) as well as an unexpected 1.2-kb product was seen. Like the 1.2-kb product observed for the reference strain *S. epidermidis* S1187 (Fig. 3 and Table 1), this band was present only in *S. epidermidis* O1B1034 when DNA was amplified using the *mphA* primer set (data not shown).

The *S. aureus* and the *E. faecalis* strains have an *erm* gene and no other erythromycin-resistant determinants; secondary evaluation of these strains using separate primer sets for the *erm* genes revealed that *S. aureus* 01A1018 had *ermA* and *E. faecalis* 03A1069 had *ermB* (data not shown). PCR analyses with two *S. pyogenes* and two *S. pneumoniae* strains revealed that one isolate of each species contains a prototypical *ermB* gene while the other isolate has the novel *mefA/E* gene.

DISCUSSION

This paper describes PCR primers that can be used to survey erythromycin-resistant mechanisms present in clinical isolates. Utilization of the multiplex PCR technology in the clinical

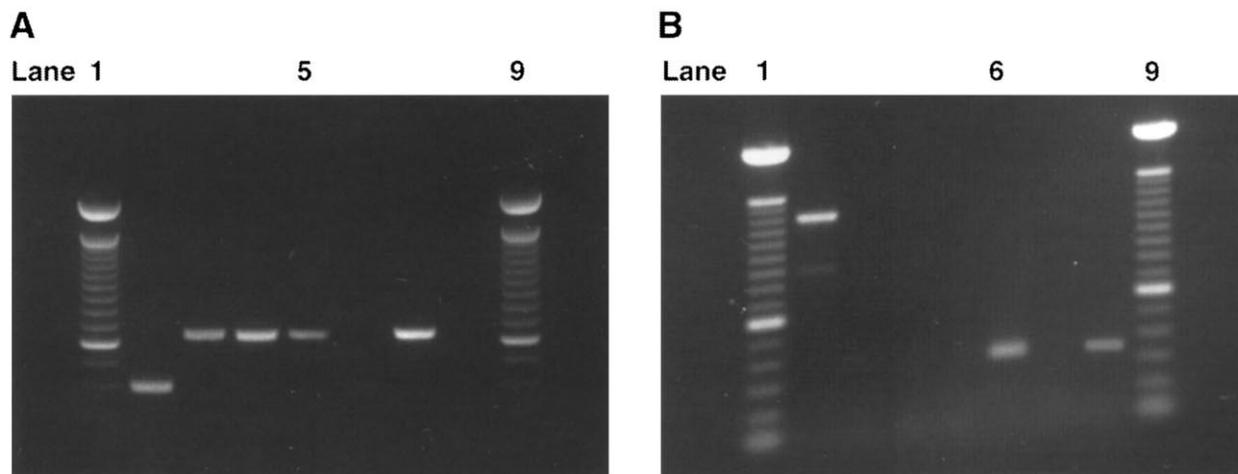


FIG. 4. PCR analysis of erythromycin-resistant determinants with clinical strains. (A) PCR products observed using primer mix I (*ermA*, *ermB*, *ermC*, *msrA/msrB*); (B) PCR products observed using primer mix II (*ereA*, *ereB*, *mphA*, *mefA/E*). Source of DNA for each lane: lanes 1 and 9, 1-kb DNA ladder; lane 2, *S. epidermidis* O1B1034; lane 3, *S. aureus* 01A1018; lane 4, *E. faecalis* 03A1069; lane 5, *S. pyogenes* 02C1076; lane 6, *S. pyogenes* 02C1086; lane 7, *S. pneumoniae* 02J1126; lane 8, *S. pneumoniae* 02J1092. See Table 2 for origin of clinical strains.

laboratory in combination with the recommended National Committee for Clinical Laboratory Standards guidelines (35) would better enable physicians to prescribe appropriate antibiotic therapy, leading to therapeutic success, more prudent antibiotic usage, and conditions less conducive to resistance selection.

From a discovery perspective, this methodology permits the direct sequencing of amplified PCR products to yield partial gene sequences for comparison from many different bacterial species. The ability to combine different primer sets in a multiplex reaction not only allows the detection of erythromycin-resistant determinants but provides a ready means for distinguishing the nature of the resistance determinant. Although the primers were designed to be specific, the nature of the cycling conditions favors sufficient promiscuity to detect closely related elements. An example of this became evident when we detected a putative *mphA*-like determinant in *S. epidermidis* S1187 (Fig. 3 and Table 1) and 01B1034 (Fig. 4 and Table 2).

The PCR multiplex methodology to detect resistance determinants can be made more powerful when combined with hybridization and sequencing studies. The success of the PCR approach alone may, however, follow reports that have recently surfaced describing PCR protocols that are as reliable as pulsed-field gel electrophoresis for strain serotyping (30) or that are sufficient to diagnose species-specific determinants (48).

ACKNOWLEDGMENTS

We thank the following people for providing reference strains: Ellen Murphy (*S. aureus* RN1389), Don Clewell [*S. pyogenes* AC1 (pAC1) and *E. faecalis* JH2-2 (pJH1)], Anne Eady (*S. epidermidis* S1187), Patrice Courvalin [*E. coli* BM694 (pAT63), BM694 (pAT72), BM2570, and BM2506 and *S. aureus* RN450 (p1524)], Koji O'Hara (*E. coli* L441D), and Ellen Smith Moland (*S. pneumoniae* 02J1175).

REFERENCES

- Allignet, J., V. Loncle, and N. El Sohl. 1992. Sequence of a staphylococcal plasmid gene, *vga*, encoding a putative ATP-binding protein involved in resistance to virginiamycin A-like antibiotics. *Gene* **117**:45–51.
- Arthur, M., A. Andremont, and P. Courvalin. 1987. Distribution of erythromycin esterase and rRNA methylase genes in members of the family *Enterobacteriaceae* highly resistant to erythromycin. *Antimicrob. Agents Chemother.* **31**:404–409.
- Arthur, M., D. Autissier, and P. Courvalin. 1986. Analysis of the nucleotide sequence of the *ereB* gene encoding the erythromycin esterase type II. *Nucleic Acids Res.* **14**:4987–4999.
- Arthur, M., and P. Courvalin. 1986. Contribution of two different mechanisms to erythromycin resistance in *Escherichia coli*. *Antimicrob. Agents Chemother.* **30**:694–700.
- Arthur, M., C. Molinas, C. Mabilat, and P. Courvalin. 1990. Detection of erythromycin resistance by the polymerase chain reaction using primers in conserved regions of *erm* rRNA methylase genes. *Antimicrob. Agents Chemother.* **34**:2024–2026.
- Ausubel, F. M., R. Brent, R. E. Kingston, D. D. Moore, J. G. Seidman, J. A. Smith, and K. Struhl. 1987. Current protocols in molecular biology, vol. 1, p. 2.4.1–2.4.4. John Wiley & Sons, New York.
- Barthelemy, P., D. Autissier, G. Gerbaud, and P. Courvalin. 1984. Enzymic hydrolysis of erythromycin by a strain of *Escherichia coli*. *J. Antibiot.* **37**:1692–1696.
- Breiman, R. F., J. C. Butler, F. C. Tenover, J. A. Elliott, and R. R. Facklam. 1994. Emergence of drug-resistant pneumococcal infections in the United States. *JAMA* **271**:1831–1835.
- Brisson-Noel, A., M. Arthur, and P. Courvalin. 1988. Evidence for natural gene transfer from gram-positive cocci to *Escherichia coli*. *J. Bacteriol.* **170**:1739–1745.
- Catchpole, I., C. Thomas, A. Davies, and K. G. H. Dyke. 1988. The nucleotide sequence of *Staphylococcus aureus* plasmid pT48 conferring inducible macrolide-lincosamide-streptogramin B resistance and comparison with similar plasmids expressing constitutive resistance. *J. Gen. Microbiol.* **134**:697–709.
- Ceglowski, P., A. Boitsov, S. Chai, and J. C. Alonso. 1993. Analysis of the stabilization system of pSM19035-derived plasmid pBT233 in *Bacillus subtilis*. *Gene* **136**:1–12.
- Clancy, J., J. Petitpas, F. Dib-Hajj, W. Yuan, M. Cronan, A. V. Kamath, J. Bergeron, and J. A. Retsema. Molecular cloning and functional analysis of a novel macrolide-resistance determinant, *mefA*, from *Streptococcus pyogenes*. *Mol. Microbiol.*, in press.
- Clewell, D. B., and A. E. Franke. 1974. Characterization of a plasmid determining resistance to erythromycin, lincomycin, and vernamycin B_α in a strain of *Streptococcus pyogenes*. *Antimicrob. Agents Chemother.* **5**:534–537.
- Eady, E. A., J. I. Ross, J. L. Tipper, C. E. Walters, J. H. Cove, and W. C. Noble. 1993. Distribution of genes encoding erythromycin ribosomal methylases and an erythromycin efflux pump in epidemiologically distinct groups of staphylococci. *J. Antimicrob. Chemother.* **31**:211–217.
- El Sohl, N., J. M. Fouace, Z. Shalita, D. H. Bouanchaud, R. P. Novick, and Y. A. Chabbert. 1980. Epidemiological and structural studies of *Staphylococcus aureus* R plasmids mediating resistance to tobramycin and streptogramin. *Plasmid* **4**:117–120.
- Garnier, T., and S. T. Cole. 1986. Characterization of a bacteriocinogenic plasmid from *Clostridium perfringens* and molecular genetic analysis of the bacteriocin-encoding gene. *J. Bacteriol.* **168**:1189–1196.
- Hagman, K. E., W. Pan, B. G. Spratt, J. T. Balthazar, R. C. Judd, and W. M. Shafer. 1995. Resistance of *Neisseria gonorrhoeae* to antimicrobial hydrophobic agents is modulated by the *mrRCDE* efflux system. *Microbiology* **141**:611–622.
- Horinouchi, S., W.-H. Byeon, and B. Weisblum. 1983. A complex attenuator regulates inducible resistance to macrolides, lincosamides, and streptogramin type B antibiotics in *Streptococcus sanguis*. *J. Bacteriol.* **154**:1252–1262.
- Horinouchi, S., and B. Weisblum. 1982. Nucleotide sequence and functional map of pE194, a plasmid that specifies inducible resistance to macrolide, lincosamide, and streptogramin type B antibiotics. *J. Bacteriol.* **150**:804–814.
- Jacob, A. E., and S. J. Hobbs. 1974. Conjugal transfer of plasmid-borne multiple antibiotic resistance in *Streptococcus faecalis* var. *zymogenes*. *J. Bacteriol.* **117**:360–372.
- Janosi, L., Y. Nakajima, and H. Hashimoto. 1990. Characterization of plasmids that confer inducible resistance to 14-membered macrolides and streptogramin type B antibiotics in *Staphylococcus aureus*. *Microbiol. Immunol.* **34**:723–735.
- Jenssen, W. D., S. Thakker-Varia, D. T. Dubin, and M. P. Weinstein. 1987. Prevalence of macrolides-lincosamides-streptogramin B resistance and *erm* gene classes among clinical strains of staphylococci and streptococci. *Antimicrob. Agents Chemother.* **31**:883–888.
- Kim, S.-K., M.-C. Baek, S.-S. Choi, B.-K. Kim, and E.-C. Choi. 1996. Nucleotide sequence, expression and transcriptional analysis of the *Escherichia coli mphK* gene encoding macrolide-phosphotransferase K. *Mol. Cells* **6**:153–160.
- Kono, M., K. O'Hara, and T. Ebisu. 1992. Purification and characterization of macrolide 2'-phosphotransferase type II from a strain of *Escherichia coli* highly resistant to macrolide antibiotics. *FEMS Microbiol. Lett.* **97**:89–94.
- Lampson, B. C., and J. T. Parisi. 1986. Naturally occurring *Staphylococcus epidermidis* plasmid expressing constitutive macrolide-lincosamide-streptogramin B resistance contains a deleted attenuator. *J. Bacteriol.* **166**:479–483.
- Leclercq, R., and P. Courvalin. 1991. Bacterial resistance to macrolide, lincosamide, and streptogramin antibiotics by target modification. *Antimicrob. Agents Chemother.* **35**:1267–1272.
- Leclercq, R., and P. Courvalin. 1991. Intrinsic and unusual resistance to macrolide, lincosamide, and streptogramin antibiotics in bacteria. *Antimicrob. Agents Chemother.* **35**:1273–1276.
- Leclercq, R., and P. Courvalin. 1993. Mechanisms of resistance to macrolides and functionally related antibiotics, p. 125–141. In A. J. Bryskier, J. P. Butzler, H. C. Neu, and P. M. Tulkens (ed.), *Macrolides—chemistry, pharmacology, and clinical uses*. Arnette, Blackwell, Paris.
- Lewis, K. 1994. Multidrug resistance pumps in bacteria: variations on a theme. *Trends Biol. Sci.* **19**:119–123.
- Louie, L., G. Papia, M. Louie, J. Talbot, and A. E. Simor. 1996. Pulsed-field gel electrophoresis (PFGE) and arbitrarily-primed polymerase chain reaction (AP-PCR) as alternatives to serotyping for *Streptococcus pneumoniae*, abstr. C-269, p. 48. In Abstracts of the 96th General Meeting of the American Society for Microbiology 1996. American Society for Microbiology, Washington, D.C.
- Matsuoka, M., L. Janosi, K. Endou, S. Saitoh, H. Hashimoto, and Y. Nakajima. 1993. An increase of 63kDa-protein present in the cell membranes of *Staphylococcus aureus* that bears a plasmid mediating inducible resistance to partial macrolide and streptogramin B antibiotics. *Biol. Pharm. Bull.* **16**:1288–1290.
- Milton, E. D., C. L. Hewitt, and C. R. Harwood. 1992. Cloning and sequencing of a plasmid-mediated erythromycin resistance determinant from *Staphylococcus xylosum*. *FEMS Microbiol. Lett.* **97**:141–147.
- Monod, M., C. Denoya, and D. A. Dubnau. 1986. Sequence and properties of pIM13, a macrolide-lincosamide-streptogramin B resistance plasmid from *Bacillus subtilis*. *J. Bacteriol.* **167**:138–147.
- Murphy, E., L. Huwyler, and M. Freire Bastos. 1985. Transposon Tn554: complete nucleotide sequence and isolation of transposition-defective and antibiotic-sensitive mutants. *EMBO J.* **4**:3357–3365.

35. **National Committee for Clinical Laboratory Standards.** 1995. Suggested groupings of U.S. FDA-approved antimicrobial agents that should be considered for routine testing and reporting on fastidious organisms by clinical microbiology laboratories, table 1A. In J. H. Jorgensen, W. A. Craig, G. V. Doern, M. J. Ferraro, S. M. Finegold, J. Fung-Tomc, S. L. Hansen, J. Hindler, D. A. Preston, L. B. Reller, J. M. Swenson, F. C. Tenover, M. A. Wikler, and W. R. Wilson (ed.), Performance standards for antimicrobial susceptibility testing, vol. 15, no. 14. National Committee for Clinical Laboratory Standards, Wayne, Pa.
36. **Nikaido, H.** 1994. Prevention of drug access to bacterial targets: permeability barriers and active efflux. *Science* **264**:382–388.
37. **Noguchi, N., A. Emura, H. Matsuyama, K. O'Hara, M. Sasatsu, and M. Kono.** 1995. Nucleotide sequence and characterization of erythromycin resistance determinant that encodes macrolide-2'-phosphotransferase I in *Escherichia coli*. *Antimicrob. Agents Chemother.* **39**:2359–2363.
38. **O'Hara, K.** 1994. Application of nuclear magnetic resonance spectrometry to measure the activity of bacterial macrolide esterase. *Microbios* **79**:231–239.
39. **O'Hara, K., T. Kanda, K. Ohmiya, T. Ebisu, and M. Kono.** 1989. Purification and characterization of macrolide 2'-phosphotransferase from a strain of *Escherichia coli* that is highly resistant to erythromycin. *Antimicrob. Agents Chemother.* **33**:1354–1357.
40. **O'Hara, K., and K. Yamamoto.** 1996. Reaction of roxithromycin and clarithromycin with macrolide-inactivating enzymes from highly erythromycin-resistant *Escherichia coli*. *Antimicrob. Agents Chemother.* **40**:1036–1038.
41. **Ounissi, H., and P. Courvalin.** 1985. Nucleotide sequence of the gene *ereA* encoding the erythromycin esterase in *Escherichia coli*. *Gene* **35**:271–278.
42. **Pan, W., and B. Spratt.** 1994. Regulation of the permeability of the gonococcal cell envelope by the *mtv* system. *Mol. Microbiol.* **11**:769–775.
43. **Projan, S. J., M. Monod, C. S. Narayanan, and D. A. Dubnau.** 1987. Replication properties of pIM13, a naturally occurring plasmid found in *Bacillus subtilis*, and of its close relative pE5, a plasmid native to *Staphylococcus aureus*. *J. Bacteriol.* **169**:5131–5139.
44. **Pujol, C., S. Ehrlich, and L. Janniere.** 1994. The promiscuous plasmids pIP501 and pAM β 1 from gram-positive bacteria encode complementary resolution functions. *Plasmid* **31**:100–105.
45. **Ross, J. I., E. A. Eady, J. H. Cove, and S. Baumberg.** 1995. Identification of a chromosomally encoded ABC-transport system with which the staphylococcal erythromycin exporter MsrA may interact. *Gene* **153**:93–98.
46. **Ross, J. I., E. A. Eady, J. H. Cove, W. J. Cunliffe, S. Baumberg, and J. C. Wootton.** 1990. Inducible erythromycin resistance in staphylococci is encoded by a member of the ATP-binding transport super-gene family. *Mol. Microbiol.* **4**:1207–1214.
47. **Ross, J. I., A. M. Farrell, E. A. Eady, J. H. Cove, and W. J. Cunliffe.** 1989. Characterisation and molecular cloning of the novel macrolide-streptogramin B resistance determinant from *Staphylococcus epidermidis*. *J. Antimicrob. Chemother.* **24**:851–862.
48. **Saulnier, P., E. Chachaty, F. Hilali, and A. Andreumont.** 1996. Combined gene detection and typing using a single polymerase chain reaction (PCR) in important clinical bacteria, abstr. C-267, p. 48. In Abstracts of the 96th General Meeting of the American Society for Microbiology 1996. American Society for Microbiology, Washington, D.C.
49. **Seppälä, H., A. Nissinen, Q. Yu, and P. Huovinen.** 1993. Three different phenotypes of erythromycin-resistant *Streptococcus pyogenes* in Finland. *J. Antimicrob. Chemother.* **32**:885–891.
50. **Shaw, J. H., and D. B. Clewell.** 1985. Complete nucleotide sequence of macrolide-lincosamide-streptogramin B-resistance transposon Tn917 in *Streptococcus faecalis*. *J. Bacteriol.* **164**:782–796.
51. **Sutcliffe, J., A. Tait-Kamradt, and L. Wondrack.** 1996. *Streptococcus pneumoniae* and *Streptococcus pyogenes* resistant to macrolides but sensitive to clindamycin: a common resistance pattern mediated by an efflux system. *Antimicrob. Agents Chemother.* **40**:1817–1824.
52. **Tait-Kamradt, A., J. Clancy, M. Cronan, F. Dib-Hajj, L. Wondrack, W. Yuan, and J. Sutcliffe.** Cloning of a macrolide efflux determinant, *mefE*, in *S. pneumoniae*. Submitted for publication.
53. **Trieu-Cuot, P., C. Poyart-Salmeron, C. Carlier, and P. Courvalin.** 1990. Nucleotide sequence of the erythromycin resistance gene of the conjugative transposon Tn1545. *Nucleic Acids Res.* **18**:3660.
54. **Weisblum, B.** 1995. Erythromycin resistance by ribosome modification. *Antimicrob. Agents Chemother.* **39**:577–585.
55. **Welby, P. E., D. S. Keller, J. L. Cromien, P. Tebas, and G. A. Storch.** 1994. Resistance to penicillin and non- β -lactam antibiotics of *Streptococcus pneumoniae* at a children's hospital. *Pediatr. Infect. Dis. J.* **13**:281–287.
56. **Wondrack, L., M. Massa, B. V. Yang, and J. Sutcliffe.** 1996. A clinical strain of *Staphylococcus aureus* inactivates and effluxes macrolides. *Antimicrob. Agents Chemother.* **40**:992–998.
57. **Wondrack, L., and J. Sutcliffe.** 1995. *Staphylococcus* strains with MS phenotype efflux and inactivate erythromycin, a 14-membered macrolide, abstr. A-84, p. 158. In Abstracts of the 95th General Meeting of the American Society for Microbiology 1995. American Society for Microbiology, Washington, D.C.