Antibiotic Susceptibility of *Tropheryma whipplei* in MRC5 Cells

Areen Boulos, Jean-Marc Rolain, and Didier Raoult*

Unité des Rickettsies, CNRS UMR 6020, IFR48, Faculté de Médecine, Université de la Méditerranée, 13385 Marseille Cedex 05, France

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Whipple’s disease is considered a rare chronic disease with a broad spectrum of clinical manifestations. Several antibiotics have been used for the treatment of this disease, and the current reference treatment was determined empirically on the basis of only a few clinical observations. Patients should be treated for months, and many relapse after antibiotic withdrawal. We report here the first extensive study on the susceptibilities of three reference strains of *Tropheryma whipplei* to antibiotics in cell culture by using a real-time PCR assay as previously described. We found that doxycycline, macrolides, ketolides, aminoglycosides, penicillin, rifampicin, teicoplanin, chloramphenicol, and trimethoprim-sulfamethoxazole were active, with MICs ranging from 0.25 to 2 μg/ml. Vancomycin was somewhat active at an MIC of 10 μg/ml. We found heterogeneity in the susceptibility to imipenem, with one strain being susceptible and the other two strains being resistant. Cephalosporins, colimycin, aztreonam, and fluoroquinolones were not active. We also demonstrated that a combination of doxycycline and hydroxychloroquine was bactericidal. This combination has been shown to be active in the treatment of patients suffering from chronic infections with *Coxiella burnetii*, a bacterium that is also found intracellularly in acidic vacuoles. We believe, then, that this combination therapy should be further evaluated in clinical trials for the treatment of Whipple’s disease.

Whipple’s disease is a chronic systemic infection affecting mostly middle-aged males (28, 33). Although first described in 1907 (35), it is a rare disease with fewer than 1,000 cases reported (8). There is a wide heterogeneity of clinical manifestations, including a prodomal period of polyarthritis, fatigue, weight loss, and anemia, which is followed by a progressive syndrome of abdominal pain and distention, steatorrhea, and severe cachexia (15). Other clinical manifestations that have been reported include endocarditis, myocarditis, pericarditis, and neurological signs.

The agent of Whipple’s disease, *Tropheryma whipplei*, has recently been isolated in a cell culture from a patient with endocarditis (24). This has enabled a more complete characterization of the organism which is an aerobic, rod-shaped, gram-positive, filamentous bacterium (0.5 to 2 μm) that can be found both intracellularly and extracellularly (8). Of note is the fact that these bacteria grow slowly in acidic vacuoles of cells (12), a finding which has also been described with other strict intracellular bacteria—in particular, *Coxiella burnetii*—that also leads to chronic infections that are difficult to treat (19). Moreover, during the cell culture the bacteria leads to the production of cords in extracellular medium (4, 8, 15, 23). It has therefore been suggested that the bacteria could have an extracellular life cycle (29).

Phylogenetically, *T. whipplei* is classified as a member of the *Actinomycetes* and has been placed between the genus *Cellulomonas* and the *Actinomycetes* clade (16). The complete genome of the bacteria has recently been sequenced, which has confirmed its phylogenetic position (1, 27).

Definitive diagnosis of Whipple’s disease is now possible by various methods, including immunohistochemistry and PCR assays for various target genes on biopsy samples (8). The PCR assay has become an important diagnostic tool for the diagnosis of Whipple’s disease, especially in patients with unusual presentations and in patients in which the diagnosis cannot be confirmed histologically.

The currently recommended treatment for Whipple’s disease has been determined empirically. The reference treatment is a combination of streptomycin (1 g) and benzylpenicillin (penicillin G; 1.2 million units) for 14 days and thereafter oral cotrimoxazole (trimethoprim-sulfamethoxazole; 160 mg/800 mg twice daily) for 1 year (14, 31). With this treatment regimen, however, relapses have been reported after cessation of antibiotic therapy (5, 11, 17). Dykman et al. have suggested that this may be because trimethoprim-sulfamethoxazole is only bacteriostatic despite the high intracellular concentrations the drug achieves (5). The use of bactericidal antibiotics may then be more appropriate in the treatment of Whipple’s disease (5, 8).

We recently developed a new genomic assay for the determination of antibiotic susceptibilities by using the LightCycler instrument (18) and found that *T. whipplei* was naturally resistant to fluoroquinolones due to specific mutations within the DNA gyrase gene (18). In the experiments we now report, we used this technique to evaluate the activity of other antibiotics against three isolates of *T. whipplei*. Previous studies have shown that alkalization of the acidic vacuoles in which *C. burnetii* and *Staphylococcus aureus* are found promotes bactericidal activity in vitro (19, 25). Since *T. whipplei* also occurs in acidic vacuoles, we evaluated the bactericidal effect of a combination of doxycycline and alkalizing agents on the organism. Such a combination has previously been shown to be active against *C. burnetii* and *S. aureus* (19, 25).
TABLE 1. T. whipplei strains and patient characteristics

<table>
<thead>
<tr>
<th>Patient sex (age [yr])</th>
<th>Strain</th>
<th>Symptoms</th>
<th>Biopsy sample</th>
<th>Antibiotic treatment before sampling</th>
<th>No. of passages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male (42)</td>
<td>Twist</td>
<td>Endocarditis</td>
<td>Cardiac valve</td>
<td>Gentamicin plus ampicillin (4 wk), ciprofloxacin (several wk)</td>
<td>50</td>
</tr>
<tr>
<td>Female (74)</td>
<td>Slow2</td>
<td>Diarrhea, arthralgia</td>
<td>Duodenum</td>
<td>None</td>
<td>33</td>
</tr>
<tr>
<td>Male (63)</td>
<td>Endo-5</td>
<td>Endocarditis</td>
<td>Blood</td>
<td>Gentamicin plus amoxicillin (3 wk)</td>
<td>44</td>
</tr>
</tbody>
</table>

MATERIALS AND METHODS

T. whipplei strains. Three T. whipplei isolates obtained in our laboratory and cultured in MRC5 fibroblast cells (ATCC number CCL-171) were tested in our study: Twist, isolated from a heart valve (24) and passed 50 times; Endo-5 (6), isolated from a heart valve and passed 44 times; and Slow2 (6), isolated from a duodenal biopsy and passed 33 times. These data are presented in Table 1.

T. whipplei-infected MRC5 cells were grown in 150-cm² culture flasks (Falcon; Beckman) incubated at 37°C in a 5% CO₂-enriched atmosphere. Minimal essential medium (Life Technologies/Gibco-BRL and Cergy Pontoise) supplemented with 10% fetal bovine serum and 2 mM l-glutamine (Gibco) was used as the incubation medium (15). Cell infection rates were monitored three times a week by examining cells scraped from the flasks and stained with Gimenez stain (13).

Antibiotic solutions. The antibiotics used in the study were tested in serial twofold dilutions as follows: doxycycline (0.5 to 8 μg/ml; Pfizer, Neuilly, France), levofloxacin (2 to 8 μg/ml; Hoechst Marion Roussel, Romainville, France), ofloxacin (0.5 to 8 μg/ml; Bayer Pharma, Sebs, France), erythromycin (0.06 to 10 μg/ml; Abbot, Rungis, France), telithromycin (0.5 to 8 μg/ml; Hoechst Marion Roussel), thiampenicol (0.06 to 32 μg/ml; Sanofi Winthrop, Gentilly, France), rifampin (0.5 to 8 μg/ml; Cassenne, Puteaux, France), trimethoprim-sulfamethoxazole (0.06 to 32 μg/ml; Roche, Paris, France), gentamicin (0.25 to 10 μg/ml; Dakota Pharm, Creteil, France), amoxicillin (0.25 to 8 μg/ml; SmithKline Beecham, Nanterre, France), streptomycin (0.25 to 8 μg/ml; Diamant, Gentilly, France), ceftriaxone (1 to 2 μg/ml; Roche, Paris, France), penicillin G (1 to 100 μg/ml; C. A calibration curve for DNA quantification was established by amplifying 10-fold serial dilutions of DNA extracted from the primary MRC5 cell inoculum used to infect MRC5 cells. The specificity of the PCR products was verified by sequencing as previously described (18).

RESULTS

Sensitivity and specificity. Figure 1 shows the melting curves obtained with standard concentrations of a previously quantified inoculum of T. whipplei (10³) and the specificity of the PCR product (a single sharp melting temperature obtained at ca. 87.5°C), as determined by using a standard calibration curve obtained with 10-fold serial dilutions of T. whipplei. The standard curve was determined in each experiment to enable the results of all experiments to be correlated. After resolution by agar electrophoresis, all T. whipplei PCR products showed a single band fragment. Sequences of this unique band were always 100% identical to the sequence of the ITS gene of T. whipplei (GenBank accession number AF248312).

Growth kinetics of T. whipplei as determined by using real-time PCR. Fibroblast cells present a contact inhibition when monolayers are confluent, and thus the numbers of cells in
each well were approximately the same (Fig. 2). The viability of cells was verified by dye staining. The growth of *T. whipplei* isolates was slow, with $2.3 \pm 3.8$ log increases in bacterial concentration over 12 days of incubation for Twist strain, $4.3 \pm 4.65$ log for Endo2 strain, and $1.8 \pm 5.4$ log for Slow2 strain. During this period, the doubling time of *T. whipplei* Twist was determined to be 35 h, whereas that of Endo2 was 32 h and that of Slow2 was of 48 h. Thereafter, bacterial growth plateaued.

**Antibiotic susceptibility testing of *T. whipplei* strains.** To be sure that the decrease in DNA copies when infected cells were treated by antibiotics was not due to a loss of viability, we have added in each PCR experiment controls, including the infected cells without antibiotics at day 0 and at day 12. Antibiotic susceptibilities against the three isolates by using real-time PCR were determined on day 12 because the three isolates reached their maximum growth after this time. This was confirmed by Gimenez staining. The three isolates of *T. whipplei*
had a similar pattern of antibiotic susceptibility (Table 2). They were susceptible to doxycycline, macrolides, telithromycin, penicillin G, streptomycin, rifampin, teicoplanin, chloramphenicol, thiamphenicol, amoxicillin, and trimethoprim-sulfamethoxazole, with MICs ranging between 0.25 and 2 μg/ml. We found heterogeneity in the susceptibility to imipenem with the Twist strain being susceptible (MIC of 0.5 μg/ml), whereas Endo2 and Slow isolates were resistant (MIC of 10 μg/ml). To vancomycin the MICs were 10 μg/ml for the three strains.

Antibiotics that were less active were cephalotin, colomycin, aztreonam, and the fluoroquinolones.

Antibiotic dilutions were found to be stable for 15 days and had the same activity against control strains over this time in the control experiments.

**Bactericidal activity of combined therapy.** Cultures of Twist strain treated with doxycycline (2 μg/ml) alone or doxycycline (2 μg/ml) and hydroxychloroquine (1 μg/ml) for 12 days, were reinoculated onto fresh confluent cells without antibiotics to evaluate the regrowth of the bacteria. The results of this experiment are shown in Fig. 3. The combination of doxycycline and hydroxychloroquine appeared to be bactericidal since no bacterial regrowth was detected by Gimenez staining or PCR assay, even after 10 days of subculture. When used alone, doxycycline was not bactericidal since regrowth of organisms occurred after 10 days of subculture as detected by PCR assay (+1.65 log of DNA copies) and also by Gimenez staining.

**DISCUSSION**

Since *T. whipplei* are obligate intracellular gram-positive bacteria, cell culture systems are required for in vitro studies of antibiotic susceptibility. The phenotypic assays usually used to determine the antibiotic susceptibility of intracellular bacteria are not suitable for *T. whipplei*, and thus we recently developed a genotypic assay using the LightCycler instrument (18). This assay enabled us to demonstrate the natural resistance of *T. whipplei* to fluoroquinolones. The resistance is associated with mutations in the DNA gyrase gene that is the target for this class of antibiotic (18). In the present study, we used the same method to assess the activity of a wide range of antibiotics encompassing members of almost all of the available antibiotic classes. We confirmed the specificity of the primers we used for the ITS gene with our findings that the PCR products obtained were always 100% identical to those of *T. whipplei*. Growth kinetics of the three isolates were similar to those described in our previous report (18). Determination of MICs was carried out in duplicate in three different experiments and results were always consistent. Our assay was thus reproducible and enabled us to determine the MICs of antibiotics precisely. We report for the first time an extensive study on the susceptibility of *T. whipplei* in cell culture to antibiotics.

Although most antibiotics were active, doxycycline, cotrimoxazole, rifampin, penicillin, macrolides, and aminoglycosides were particularly active. These results, apart from those for the penicillins, are consistent with our current knowledge.

**TABLE 2. MICs of antibiotics active against *T. whipplei* as determined by Light Cycler assay**

<table>
<thead>
<tr>
<th>Antibiotic</th>
<th>Twist</th>
<th>Endo-5</th>
<th>Slow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penicillin G</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Amoxicillin</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Rifampin</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Erythromycin</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Clarithromycin</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Telithromycin</td>
<td>0.25</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Doxycycline</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sulfamethoxazole-trimethoprim</td>
<td>2/0.5</td>
<td>4/1</td>
<td>4/1</td>
</tr>
<tr>
<td>Teicoplanin</td>
<td>0.25</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Vancomycin</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Streptomycin</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Gentamicin</td>
<td>4</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Thiamphenicol</td>
<td>0.25</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>Chloramphenicol</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Imipenem</td>
<td>0.5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Aztreonam</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Cephalotin</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Ceftriaxone</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Colimycin</td>
<td>20</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Levofloxacin</td>
<td>0.25</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Ofloxacin</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Ciprofloxacin</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Hydroxychloroquine</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>
of antibiotic activity against intracellular bacteria (21). Indeed, doxycycline, rifampin, macrolides, and aminoglycosides have been shown to be highly active against strict intracellular bacteria such as Rickettsia spp., C. burnetii, and Ehrlichia spp. (21, 22, 32). Of note is our finding that trimethoprim-sulfamethoxazole was active. The target for trimethoprim is dihydrofolate reductase, the coding sequence of which has recently been shown to be absent from the genome of T. whipplei (3). The activity of trimethoprim-sulfamethoxazole in our study was therefore likely to be due to an effect of the sulfonamide compound alone. Dihydropyruvotransynthetase, the target gene for sulfamethoxazole, occurs in both the genome sequences available for T. whipplei. This activity is similar to that reported for bacteria of the genus Nocardia spp. (34). We found that penicillin compounds were active against T. whipplei, although this class of antibiotics usually have poor penetration into cells. Their activity could be due to the inhibition of growth of extracellular bacteria (15, 29, 30) since supernatants of cultures treated with penicillins were free of the extracellular form of the bacteria (data not shown).

The heterogeneity of susceptibility to imipenem that we found was very surprising because susceptibility to penicillin G and resistance to imipenem has not been described previously. Resistance to imipenem has been reported in other gram-positive bacteria, including Enterococcus, Nocardia, and Corynebacteria spp. (10). The mechanisms whereby T. whipplei are resistant to imipenem are unknown, but it could be due to alterations in penicillin-binding proteins, to the presence of zinc metalloprotease (beta-lactamase), to efflux mechanisms, or to intracellular inactivation of the drug (10).

Among glycopeptide compounds, although teicoplanin was active, we found a low level of resistance to vancomycin (MICs of 10 µg/ml). This discrepancy in activity has been reported previously for bacteria in the genus Enterococcus due to the acquisition of vanC or vanE operons, which code for ligases (2). The vanE operon, in particular, confers resistance to vancomycin, whereas teicoplanin and ampicillin remain active (2, 9). Of interest is our finding of a D-Ala-D-Ala ligase (GenBank accession number NP_789196) in the genome of T. whipplei, which has 32% homology with the vanE operon from E. faecalis (GenBank accession number AAL27442.1) and could be involved in the mechanism of resistance in T. whipplei.

Antibiotics found to be less active in our study were cephalotin, colimycin, aztreonam, and fluoroquinolones. This poor activity could be due either to a poor penetration in the cells, to an intracellular interaction, or to efflux mechanisms. The clear explanation of this poorer activity is not known except for the fluoroquinolones, for which there are specific mutations within the DNA gyrase gene involved in resistance (18). Our results are in accordance with our recent report showing that these antibiotics may be used to decontaminate samples from which T. whipplei is to be isolated in cell culture (6).

Based on our knowledge of the activity of antibiotics against C. burnetii, a bacterium that also exists in intracellular acidic vacuoles (12), we tested the in vitro bactericidal effect of a combination of doxycycline and hydroxychloroquine on the organism. Alkalination of the vacuoles has been shown to result in a bactericidal activity of doxycycline against C. burnetii (19, 25) and S. aureus (20). We also found that this also occurred with T. whipplei and that the bacteria were killed when a combination of doxycycline and hydroxychloroquine were used. This finding could help to better define the optimum treatment of Whipple’s disease. Most patients suffering from chronic Whipple’s disease may have their disease controlled by various antibiotic regimens, but the disease often recurs after antibiotic withdrawal. We believed that these treatment failures are due to a lack of bactericidal activity of the antibiotics used in therapy. This has been also demonstrated in patients with chronic Q fever (26). Because C. burnetii and T. whipplei both occur in acidic vacuoles of the cell during chronic infections, we suggest that our knowledge of the treatment of Q fever should be applied to Whipple’s disease. Clinical multicentric trials using combination therapy with doxycycline and hydroxychloroquine as the main treatment of Whipple’s disease will be needed to prove our hypothesis.

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19 patients from one hospital and a review of the literature since 1950. Medicine 49:175–205.


