INTRODUCTION

Obligately anaerobic bacteria comprise the largest part of the physiological flora on skin and mucous membranes of humans. Since they are opportunistic pathogens, they often participate in endogenous infections, causing mixed infections together with aerobic bacteria. Such infections (i.e. intra-abdominal) are burdened with high morbidity and mortality, and require treatment with antimicrobial drugs showing activity against both aerobic and anaerobic bacteria (Gorbach, 1994; Nathens & Rotstein, 1996; Olsen et al., 1999).

Moxifloxacin is a quinolone that, like trovafloxacin and clinafloxacin, belongs to the fluoroquinolone group IV as defined by Naber & Adam (1998). It has an antimicrobial activity against many Gram-positive and Gram-negative aerobic and anaerobic bacteria as well as atypical bacteria such as Chlamydia and Mycoplasma (Dalhoff et al., 1996; Bauernfeind, 1997; Goldstein et al., 1997; Edlund et al., 1998; Ackermann et al., 2000; Blondeau et al., 2000; Schaumann et al., 2000; Kleinkauf et al., 2001; Krasemann et al., 2001; Talan, 2001; Zhanel et al., 2002).

Several in vitro studies have indicated that moxifloxacin has good in vitro activity against important anaerobic bacteria especially Bacteroides species (Edlund et al., 1998; Ackermann et al., 2000). However, compared to the activities of garenoxacin, clinafloxacin, sitafloxacin and trovafloxacin, moxifloxacin more recently was the least active agent against 589 Bacteroides fragilis group isolates (Snydman et al., 2002). Furthermore, fluoroquinolone resistance among Bacteroides isolated in the USA has apparently markedly increased since 1994 (Golan et al., 2003). Hedberg & Nord (2003) reported that antimicrobial resistance among B. fragilis group isolates in Europe is also increasing. Conversely, cidal moxifloxacin activity was found for respiratory pathogens (aerobes and anaerobes) even when sera were obtained 24 h after dosing. The results suggest that moxifloxacin may have clinical utility in the treatment of mixed aerobic/anaerobic respiratory tract infections (Stein et al., 2003b). In a recently published paper investigating serum bactericidal activity of moxifloxacin and gatifloxacin, Stein et al. (2003a) reported little or no serum bactericidal activity of either drug if the MICs of gatifloxacin were $\geq 2$ mg l$^{-1}$. However, moxifloxacin was found to be effective in vivo even against a B. fragilis strain with a high MIC level for moxifloxacin in an experimental animal model of severe mixed aerobic/anaerobic infection (Schaumann et al., 2004).
The aim of the present study was to assess the killing activity of moxifloxacin in an in vitro pharmacokinetic/pharmacodynamic (PK/PD) model against four selected B. fragilis strains used previously in the in vivo experimental model (Schaumann et al., 2004). Since anaerobes are often present in mixed infections, kill kinetics were also established for mixed inocula employing the B. fragilis strains together with one of two different Escherichia coli strains, one strain with a low MIC for moxifloxacin and one with a high MIC.

METHODS

Bacterial strains. E. coli ATCC 25922, E. coli VA 6886 and different strains of B. fragilis (RMA 0309, RMA 5120, RMA 6791, WAL R 13267) were used. E. coli VA 6886 was isolated from bile at the Institute of Medical Microbiology of Leipzig, Germany. RMA 0309 and RMA 5120 were intra-abdominal isolates, RMA 6791 was a blood culture isolate and WAL R 13267 was a clinical isolate of unknown origin.

The B. fragilis strains and E. coli ATCC 25922 strain were characterized as follows as described previously (Schaumann et al., 2004): B. fragilis RMA 0309, enterotoxin negative, MIC for moxifloxacin 0·125 mg l\(^{-1}\); B. fragilis RMA 5120, enterotoxin negative, MIC for moxifloxacin 0·125–0·38 mg l\(^{-1}\); B. fragilis RMA 6791, enterotoxin positive, MIC for moxifloxacin 0·25–0·5 mg l\(^{-1}\); B. fragilis WAL R 13267, enterotoxin positive, MIC for moxifloxacin >32 mg l\(^{-1}\); E. coli ATCC 25922, MIC value for moxifloxacin <0·03 mg l\(^{-1}\).

The MIC for the E. coli strain VA 6886 was established by broth microdilution technique according to DIN 58940-8 (Deutsches Institut für Normung e.V., 2000). The result was confirmed by E-test (AB BIODISK) according to the manufacturer’s instructions, resulting in a MIC value of >32 mg l\(^{-1}\).

The E. coli strains were grown on Endo agar (bioMérieux) and the B. fragilis strains were grown on Columbia agar (Oxoid) supplemented with 5 % sheep blood (Oxoid), vitamin K1 (Sigma) and haemin (Serva Feinbiochemica). After incubation, B. fragilis strains and E. coli strains were harvested from the plates and suspended separately in Brucella broth (Becton Dickinson) supplemented with vitamin K1 and haemin, and incubated overnight at 37 °C under anaerobic and aerobic conditions, respectively. Then the suspensions were adjusted turbidimetrically to contain approximately 1·2 × 10\(^8\) c.f.u. ml\(^{-1}\) B. fragilis and approximately 1·5 × 10\(^8\) c.f.u. ml\(^{-1}\) E. coli. Cultures for the experimental model were set up as described below and the numbers of bacteria were confirmed by appropriate plating.

Antimicrobial agent. Moxifloxacin powder of known activity was kindly provided by Bayer Vital and suspended in distilled water.

Experimental model. In order to determine the pharmacodynamic activity of moxifloxacin all six strains were investigated in pure cultures as well as in mixed cultures. Cultures were set up in a final volume of 20 ml of appropriately supplemented Brucella broth with approximately 2·4 × 10\(^8\) c.f.u. ml\(^{-1}\) B. fragilis or approximately 3 × 10\(^8\) c.f.u. ml\(^{-1}\) E. coli or both, and an initial maximum concentration (C\(_{\text{max}}\)) of 4·0 mg l\(^{-1}\) moxifloxacin. The in vitro pharmacokinetic assays for moxifloxacin were carried out over 12 h with \(t_{1/2}\) of 13 h according to the equation \(C_t = C_0 \times e^{-k_d t} \times t\) (\(C_t\) = concentration of moxifloxacin at a given point in time (t); \(C_0\) = initial concentration of moxifloxacin). The elimination rate constant (\(k_d\)) was calculated using the equation \(k_d = \ln 2/t_{1/2}\).

An observation time period of 12 h was chosen according to the half-life of moxifloxacin and the dosing interval suggested for intra-abdominal infections. We used a C\(_{\text{max}}\) concentration for moxifloxacin of 4 mg l\(^{-1}\) equal to total concentration since protein binding of moxifloxacin probably occurs in culture media as well. High inocula of approximately 2·4 × 10\(^8\) c.f.u. ml\(^{-1}\) B. fragilis and approximately 3 × 10\(^7\) c.f.u. ml\(^{-1}\) E. coli were used since abscesses contain a large number of bacteria (Stearne et al., 2001 & 2002).

The PK/PD model was established by adding appropriate amounts of supplemented Brucella broth every 30 min (540–980 μl), resulting in a final volume of 36·25 ml and a final moxifloxacin concentration of 2·11 mg l\(^{-1}\) after 12 h. At 30 min intervals samples (20 μl) were taken and diluted aliquots were plated on Endo agar as well as on supplemented Columbia agar. The experiments were carried out in an anaerobic chamber (Heraeus) containing 80 % N\(_2\), 15 % CO\(_2\) and 5 % H\(_2\) at 37 °C. However, the Endo agar plates were incubated under aerobic conditions for 24 h. After incubation, bacterial colonies were counted and calculated to colony forming units per ml. The detection limit was 1 × 10\(^2\) c.f.u. ml\(^{-1}\). In mixed cultures it was macroscopically possible to distinguish the colonies of E. coli from the colonies of B. fragilis strains growing on Columbia agar due to morphological criteria.

Statistical analysis. Mann trend test was used for testing for trends in a time-series of killing ratios (Hartung, 1994; Hollander & Wolfe, 1999). A P value of <0·05 was considered to be significant.

RESULTS AND DISCUSSION

For our PK/PD assay we employed a reasonably high initial concentration of moxifloxacin (4 mg l\(^{-1}\)) that was reduced to approximately 2·11 mg l\(^{-1}\) after 12 h. In pure cultures the bacterial numbers of B. fragilis strains with low MICs (≤0·5 mg l\(^{-1}\)) were moderately but significantly reduced (by about one to two logs) by moxifloxacin within 12 h (killing rates: RMA 0309, 99·3 %; RMA 5120, 99·2 %; RMA 6791, 99·2 %; P < 0·01). For B. fragilis WAL R 13267 (MIC >32 mg l\(^{-1}\)) no reduction was observed (P > 0·05). Thus, none of the B. fragilis strains was effectively killed in pure culture (Fig. 1).

The E. coli ATCC 25922 strain (MIC <0·03 mg l\(^{-1}\)) was rapidly killed by moxifloxacin both in pure (data not shown) and mixed cultures (Fig. 2a), confirming a bactericidal effect against this strain (P < 0·01; killing rate within the first hour >99·9 %). As was to be expected, there was no bactericidal effect of moxifloxacin against the E. coli strain VA 6886 (MIC value: >32 mg l\(^{-1}\)) at the moxifloxacin concentrations employed here (Fig. 2b; P > 0·05; data of pure culture not shown).

In mixed cultures employing E. coli strain ATCC 25922, with the low moxifloxacin MIC, the bacterial numbers of B. fragilis strains with low MICs were significantly reduced (killing rates: RMA 5120, 90·5 %; RMA 6791, 91·8 %; RMA 0309, 99·8 %; P < 0·01; Fig. 2a) and the growth rate of the B. fragilis strain with a high MIC (WAL R 13267) was significantly lower compared to the control without moxifloxacin (P < 0·01). Nevertheless, in the presence of the E. coli strain ATCC 25922 the moderate activity of moxifloxacin against the anaerobes (except strain RMA 0309) was significantly reduced as compared to single anaerobic cultures (P ≤0·01). In mixed cultures containing the E. coli strain VA 6886 and the B. fragilis strains with low MICs, the bacterial
numbers of these bacteria were again significantly reduced compared to the control (killing rates: RMA 0309, 72.2%; RMA 5120, 82.7%; RMA 6791, 88.2%; \( P < 0.01 \); Fig. 2b) but significantly less reduced if compared to pure cultures with moxifloxacin (\( P < 0.01 \)). Comparing the effects of the two \( E. \) coli strains on the anaerobes a significant difference in killing was only found for \( B. \) fragilis RMA 0309 (\( P < 0.01 \)). In addition, the growth of the \( B. \) fragilis WAL R 13267 strain was significantly lower in the presence of the \( E. \) coli VA 6886 strain when compared to pure culture or to the mixed culture with \( E. \) coli ATCC 25922 (\( P < 0.01 \)). However, the growth of the \( B. \) fragilis WAL R 13267 strain was not reduced by moxifloxacin compared to the initial inoculum.

In contrast to the moderate activity of moxifloxacin investigated here using the \textit{in vitro} PK/PD model, moxifloxacin has been shown to be as efficacious as imipenem/cilastatin in the treatment of severe systemic mixed aerobic/anaerobic infection in mice using the same \( B. \) fragilis strains and \( E. \) coli strain ATCC 25922 (Schaumann \textit{et al.}, 2004). Earlier observations of Onderdonk \textit{et al.} (1976) suggested that \( E. \) coli is primarily responsible for the lethal effects in the animals. Therefore, the results of the PK/PD model support those previous observations since in the \textit{in vitro} PK/PD model, moxifloxacin was fully bactericidal against the \( E. \) coli strain ATCC 25922. The presence of the \( E. \) coli ATCC 25922 and VA 6886 strains reduced the killing activity of moxifloxacin against the \( B. \) fragilis strains investigated in the \textit{in vitro} PK/PD model. This observation is supported by earlier results obtain with trovafloxacin (Stearne \textit{et al.}, 2001). Furthermore, protection of \( B. \) fragilis against the activity of metronidazole by \textit{Enterococcus faecalis} has also been observed (Nagy & Földes, 1991). Nagy & Földes (1991) reported that metronidazole was inactivated by a cell extract of \textit{E. faecalis}. 

\textbf{Fig. 1.} Activity of moxifloxacin against four different strains of \( B. \) fragilis tested in the \textit{in vitro} PK/PD model in pure cultures with and without moxifloxacin. MXF+, with moxifloxacin; MXF−, control without moxifloxacin. Detection limit: \( 10^{2} \) c.f.u. ml\(^{-1} \).
However, inactivation of trovafloxacin by *Enterococcus faecium* was not described (Stearne *et al.*, 2001).

The reason for the different killing rates of moxifloxacin against the *B. fragilis* strains with low MICs investigated in our PK/PD model in mixed cultures is not yet understood. Stearne *et al.* (2001) discussed whether the emergence and selection of trovafloxacin-resistant mutants, with possible transfer of this resistance to *B. fragilis* in mixed infections, could account for the protection against the activity of the
antimicrobial agent. However, further investigations would be required to confirm this hypothesis. Because of the results reported here, the clinical study data obtained for moxifloxacin treatment of patients with intra-abdominal infections need intensive scrutiny.

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REFERENCES


