Novel synergistic antibiofilm combinations for salvage of infected catheters

Mohan Venkatesh, Liang Rong, Issam Raad and James Versalovic

1Section of Neonatology, Department of Pediatrics, Texas Children’s Hospital & Baylor College of Medicine, Houston, TX 77030, USA
2Department of Infectious Diseases, MD Anderson Cancer Center, Houston, TX 77030, USA
3Department of Pathology, Texas Children’s Hospital & Baylor College of Medicine, Houston, TX 77030, USA

Biofilms on catheters are responsible for catheter-related bloodstream infections (CRBSIs), which cause significant mortality and morbidity. Antimicrobial catheter-lock solutions may salvage precious catheters by eradicating biofilms. Staphylococcus epidermidis and Candida albicans are frequently isolated organisms in CRBSIs. We evaluated N-acetylcysteine (NAC), EDTA, ethanol and talactoferrin (TLF) individually and in combination with antibiotics against biofilms of S. epidermidis and C. albicans to identify effective catheter-lock solutions. Minimum biofilm-eradication concentrations causing 50 % inhibition (MBEC 50) for EDTA, NAC, ethanol and TLF were determined against biofilms of S. epidermidis and C. albicans formed on 96-well microtitre plates. Biomass, mean thickness and viability of S. epidermidis and C. albicans biofilms were evaluated after exposure to MBEC 50 concentrations of EDTA, NAC, ethanol and TLF. Antimicrobial combinations of EDTA, NAC, ethanol and TLF with nafcillin, vancomycin, fluconazole and amphotericin B were evaluated systematically for synergy using combination indices (CIs). EDTA, NAC, ethanol and TLF significantly reduced biofilm biomass and mean thickness (P < 0.05, one-way ANOVA) of monomicrobial and polymicrobial biofilms as evaluated by confocal microscopy. CIs evaluated at equipotency ratios, and 50, 75 and 90 % effects, showed that EDTA, NAC, ethanol and TLF were synergistic (CI <1) with antibiotics (with few exceptions) against biofilms of S. epidermidis and C. albicans. EDTA, NAC, ethanol and TLF inhibit monomicrobial and polymicrobial biofilms of neonatal strains of S. epidermidis and C. albicans, and are synergistic with antibiotics. Catheter-lock solutions of EDTA, NAC and ethanol alone or in combination with antibiotics may be used to salvage infected catheters, which will directly impact on patient morbidity and health-care costs.

INTRODUCTION

Biofilms on catheters are responsible for about 85 % of catheter-related bloodstream infections (CRBSIs) in intensive-care units, and cause significant mortality and morbidity (Console et al., 2007; Donelli, 2006; Pawar et al., 2004). A single episode of CRBSI is estimated to cost as much as $56 167 (£38 180) (Dimick et al., 2001; Rello et al., 2000). Removal of medical devices is often required to eradicate biofilm-associated infections (Gandelman et al., 2007). The most frequent organisms causing CRBSIs are Staphylococcus epidermidis, Staphylococcus aureus and Candida species (Raad & Hanna, 2002), and these microbes have been isolated together in biofilm-related polymicrobial infections (Karłowicz et al., 2000). The increased mortality and morbidity due to polymicrobial infections makes it imperative to evaluate new treatment modalities against polymicrobial biofilms (Faix & Kovarik, 1989; McKenzie, 2006). Hence, we evaluated monomicrobial and polymicrobial biofilms in our experimental studies.

Antimicrobial agents alone or in combination locked in the lumen of catheters for varying time periods have been effective against biofilms on intravascular catheters (Anaissie et al., 1995; Raad et al., 2003, 2007a, b) and have been recommended to prevent CRBSIs (O’Grady et al., 2002). We sought to evaluate antibiofilm agents individually and in combination with antibiotics against clinical
isolates of organisms to emphasize the utility of antimicrobial-lock combinations in the salvage of infected catheters.

The emergence of alarming levels of antibiotic resistance urged us to look at other non-antibiotic strategies against CRBSIs (Levy, 1998). We evaluated N-acetylcysteine (NAC), EDTA, ethanol and talactoferrin (TLF) (human recombinant lactoferrin). NAC is used as a mucolytic and may disrupt or prevent exopolysaccharide (EPS) formation in biofilms (Perez-Giraldo et al., 1997). EDTA, a chelator of calcium and magnesium, and an anticoagulant, inhibits planktonic Staphylococcus and Candida species (Gil et al., 1994; Root et al., 1988). Ethanol has been shown to be effective in eradicating monomicrobial biofilms without altering the mechanical properties of silicone or polyurethane catheters (Crnich et al., 2005; Raad et al., 2007a). Lactoferrin is an iron-binding glycoprotein, which is naturally present in human glandular secretions (milk, tears and saliva), and has broad-spectrum antimicrobial activity against bacteria and fungi (Valenti & Antonini, 2005).

The effects of NAC, EDTA, ethanol or lactoferrin (TLF) have not been evaluated against polymicrobial biofilms of S. epidermidis and Candida albicans. Therefore, we evaluated NAC, EDTA, ethanol and TLF on monomicrobial and polymicrobial biofilms of C. albicans and S. epidermidis. Interactions of these agents with antibiotics in combination with nafcillin, vancomycin, fluconazole and amphotericin B were evaluated for synergy. Novel antimicrobial strategies specifically targeting biofilms with synergistic antibiotic combinations are urgently needed to reduce CRBSIs and improve clinical outcomes (Furuuya & Lowy, 2003).

**METHODS**

**Organisms.** Clinical isolates of S. epidermidis (ATCC 55133, H100 and S101) and C. albicans (ATCC 32354 and MYA 4441) were used (two strains of S. epidermidis and one strain of C. albicans were isolated from septic neonates).

**Antimicrobial agents.** Antimicrobial agents were prepared as stock solutions as recommended by the Clinical and Laboratory Standards Institute (CLSI) wherever appropriate (CLSI, 2002, 2003, 2007). Dilutions were performed in the growth media appropriate for the organism and the following agents were used: (i) NAC (USB) pH adjusted to 7 and evaluated in twofold serial dilutions from 32 to 0.5 mg ml⁻¹; (ii) disodium EDTA (Sigma-Aldrich), pH adjusted to 7 and evaluated in twofold serial dilutions from 32 to 0.5 mg ml⁻¹; (iii) ethanol (AAPER Alcohol and Chemical) evaluated in twofold serial dilutions from 100 to 3%; (iv) recombinant human lactoferrin (TLF) (Agennix), evaluated in twofold serial dilutions from 66.4 to 0.125 mg ml⁻¹; (v) fluconazole (Sigma-Aldrich), evaluated in twofold serial dilutions from 128 to 0.125 μg ml⁻¹; (vi) amphotericin B (Sigma-Aldrich) evaluated in twofold serial dilutions from 128 to 0.125 μg ml⁻¹; (vii) vancomycin (USB) evaluated in twofold serial dilutions from 64 to 0.5 μg ml⁻¹; (viii) nafcillin (Sigma-Aldrich) evaluated in twofold serial dilutions from 64 to 0.5 μg ml⁻¹.

**Biofilms.** Biofilms were formed in 96-well microtitre plates by adding 100 μl S. epidermidis or C. albicans at approximately 10⁶ c.f.u. ml⁻¹ individually or 50 μl of both (for polymicrobial biofilms) in RPMI 1640 medium (pH 7) and incubating for 24 h at 35 °C. Biofilm formation was confirmed by light microscopy and 2, 3-bis(2-methoxy-4-nitro-5-sulphonyl)-2H tetrazolium-5-carboxanilide (XTT) reduction assay as reported by other investigators (Cerca et al., 2004, 2005; Ramage & Lopez-Ribot, 2005).

**Evaluation of minimum biofilm eradication concentration causing 50% inhibition (MBEC50) of single antibiotic agents.** Evaluation of the antimicrobial susceptibility of biofilms to antimicrobial agents was performed in duplicate using adapted CLSI guidelines (Domingue et al., 1994; Ramage & Lopez-Ribot, 2005). Minimum biofilm eradication concentration was defined as the minimum concentration of the antibiotic needed to eradicate 50% of the biofilm – the MBEC50. Growth and sterility controls on the same microtitre plate were used for comparison. The biofilms in the microtitre plates were exposed to the antibiotic agent for 20 h (S. epidermidis) or 48 h (C. albicans). Inhibition end point was assessed by XTT reduction assay as described by Hawser et al. (1998). Briefly, XTT (0.5 g l⁻¹ in Ringer’s lactate) and menadione (1 μM) were added to washed biofilms, incubated in the dark for 2 h at 37 °C and the colorimetric change in the supernatant was measured in a microtitre plate reader as the absorbance at 490 nm.

**Evaluation of biofilm architecture by confocal laser scanning microscopy.** Biofilms of C. albicans ATCC 32354 and S. epidermidis ATCC 55133 were formed on 4-well optical bottom glass slides. These biofilms were exposed to NAC, disodium EDTA and TLF at 8 mg ml⁻¹, ethanol at 12.5 % or growth medium (control) for 24 h. The biofilms were washed and stained with LIVE/DEAD stain and examined using a Zeiss meta confocal microscope. Serial sections in the x-y plane were obtained at 1 μm intervals along the z-axis, and the z-stack image was analysed by COMSTAT 2 software for biomass and mean thickness (Heydorn et al., 2000). Biofilms exposed to the antimicrobial agents were compared with the controls by one-way ANOVA and statistical significance was assumed at P<0.05.

**Evaluation of biofilm viability after exposure to antibiofilm agents.** Biofilms of S. epidermidis or C. albicans were formed in 96-well microtitre plates and were exposed to EDTA, NAC and TLF at 16 mg ml⁻¹, ethanol at 12.5 % or medium (control). At 0, 24, 48 and 72 h, the biofilms were scraped, sonicated ten times for 10 s and plated in serial dilutions. For polymicrobial biofilms, the dilutions were plated in triplicate and the experiment was repeated at least twice (at least six evaluations at any time point for each intervention). Results were analysed by two-way ANOVA using the Graph Pad Prism (version 4) statistical software.

**Evaluation of antimicrobial combinations for synergy.** EDTA, NAC, ethanol and TLF were combined with vancomycin and nafcillin against S. epidermidis, and with amphotericin B and fluconazole against C. albicans. Susceptibilities were evaluated in an 8-well by 8-well chequerboard format in 96-well microtitre plates. Antibiofilm agents were prepared in twofold serial dilutions across rows and columns, and inhibitory end points were assessed by the XTT reduction assay similar to evaluation of MBEC50 for single agents. Inhibitory effects at equipotent drug-dose ratios (ratios of MBEC50) of the combinations were determined. The median effects method described by Chou and colleagues was used to study interactions in drug combinations by the calculation of combination indices (CIs) (Chou & Talalay, 1984; Chou, 2006).
The median effects principle is given by the equation: $f_a/f_u = (D/D_m)^m$, where $f_a$ is the fraction affected by the drug, $f_u$ is the fraction unaffected ($f_u = 1 - f_a$), $D$ is the concentration of the drug and $D_m$ is the median effect dose [the dose of the drug that produces 50 % of the effect, i.e. the effective dose $D_m$ (ED $D_m$)]. The co-efficient of the dose–effect relationship is given by $m$, and $m=1$, $>1$ and $<1$ indicates hyperbolic, sigmoidal and flat-sigmoidal dose–effect curves, respectively.

The CI is given by the equation: $CI = (D_1/D_{m1}) + (D_2/D_{m2})$, where $(D_1)$ and $(D_2)$ are doses of drug 1 and drug 2 in combination, and $(D_{m1})$ and $(D_{m2})$ are doses of drug 1 and drug 2 that produce $x$% effect when used alone. A CI $<1$ indicates synergy, CI $>1$ antagonism and CI =1, an additive effect. Multiple drug dose–effect calculations were performed using Calcusyn software (Biosoft) (http://www.biosoft.com/w/calcusyn.htm) with constant ratios of drug combinations.

**RESULTS AND DISCUSSION**

**MBEC$_{50}$**

Antimicrobial susceptibility testing for biofilms of *C. albicans* and *S. epidermidis* have not been standardized and hence we adapted the CLSI guidelines for planktonic MIC testing to our biofilm experiments (CLSI, 2002, 2003, 2007). MBEC$_{50}$ values for NAC, disodium EDTA, ethanol and TLF were comparable to results from other investigators and are shown in Table 1 (Bachmann et al., 2003; Leitch & Willcox, 1999a; Marchese et al., 2003; Olofsson et al., 2003; Percival et al., 2005).

**Evaluation of biofilms by confocal imaging microscopy**

Confocal microscopy is frequently used in evaluating biofilm architecture and is preferred over electron microscopy because the embedding process dehydrates the biofilm specimen (Heydorn et al., 2000). We found that NAC, EDTA and TLF at 8 mg ml$^{-1}$ and ethanol at 12.5 % significantly decreased biofilm biomass, and mean thickness of monomicrobial and polymicrobial biofilms of *S. epidermidis* ATCC 55133 and *C. albicans* ATCC 32354 (Figs 1, 2 and 3) compared to controls exposed to growth medium (control) for 24 h. Biomass (a) and mean thickness (b) were evaluated by confocal microscopy and data are presented as means ± SD. NAC, EDTA, ethanol and TLF significantly decreased biofilm biomass and mean thickness compared to the controls (*P*<0.05, one-way ANOVA).

**Fig. 1.** Antibiofilm agents decrease biomass and thickness of *S. epidermidis* ATCC 55133 biofilms. *S. epidermidis* ATCC 55133 biofilms grown in optical bottom glass slides were exposed to NAC, EDTA and TLF at 8 mg ml$^{-1}$, ethanol at 12.5 % or growth medium (control) for 24 h. Biomass (a) and mean thickness (b) were evaluated by confocal microscopy and data are presented as means ± SD. NAC, EDTA, ethanol and TLF significantly decreased biofilm biomass and mean thickness compared to the controls (*P*<0.05, one-way ANOVA).

<table>
<thead>
<tr>
<th>Organism</th>
<th>NAF (µg ml$^{-1}$)</th>
<th>VAN (µg ml$^{-1}$)</th>
<th>AMB (µg ml$^{-1}$)</th>
<th>FLC (µg ml$^{-1}$)</th>
<th>EDTA (mg ml$^{-1}$)</th>
<th>NAC (mg ml$^{-1}$)</th>
<th>Ethanol (%)</th>
<th>TLF (mg ml$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. epidermidis</em> ATCC 55133</td>
<td>8</td>
<td>8</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>8</td>
<td>12.5</td>
<td>4</td>
</tr>
<tr>
<td><em>S. epidermidis</em> H100</td>
<td>8</td>
<td>16</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>1</td>
<td>12.5</td>
<td>8</td>
</tr>
<tr>
<td><em>S. epidermidis</em> S101</td>
<td>32</td>
<td>32</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>4</td>
<td>12.5</td>
<td>8</td>
</tr>
<tr>
<td><em>C. albicans</em> ATCC 32354</td>
<td>–</td>
<td>–</td>
<td>64</td>
<td>64</td>
<td>32</td>
<td>32</td>
<td>12.5</td>
<td>33.2</td>
</tr>
<tr>
<td><em>C. albicans</em> ATCC MYA 4441</td>
<td>–</td>
<td>–</td>
<td>32</td>
<td>32</td>
<td>16</td>
<td>32</td>
<td>12.5</td>
<td>66.4</td>
</tr>
<tr>
<td>Polymicrobial biofilm of <em>S. epidermidis</em> ATCC 55133 and <em>C. albicans</em> ATCC 32354</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.25</td>
<td>2</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

AMB, Amphotericin B; FLC, fluconazole; NAF, nafcillin; VAN, vancomycin.
Evaluation of the viability of polymicrobial biofilms after exposure to antibiofilm agents

We evaluated polymicrobial biofilms of *S. epidermidis* and *C. albicans*, because polymicrobial infections of the above organisms are seen in patients with intravascular catheters (Faix & Kovarik, 1989; Kaufman & Fairchild, 2004; Noyola *et al.*, 2001) but have not been adequately studied. In polymicrobial biofilms of *S. epidermidis* ATCC 55133 and *C. albicans* ATCC 32354, both organisms contributed proportionally to the biofilm at 24, 48 and 72 h (Fig. 4a). Viability of *S. epidermidis* ATCC 55133 was significantly decreased by EDTA and ethanol at 24, 48 and 72 h, by NAC at only 24 and 48 h and not by TLF (Fig. 4b). Viability of *C. albicans* ATCC 32354 was significantly reduced only by ethanol compared to the control at 24, 48 and 72 h. Other agents (EDTA, NAC and TLF) did not reduce the viability of *C. albicans* (Fig. 4c).

Ethanol significantly reduced biofilm viability in polymicrobial biofilms and monomicrobial biofilms of all *C. albicans* strains, and monomicrobial biofilms of two strains of *S. epidermidis* after 24, 48 and 72 h of exposure (Supplementary Figs S1 and S2 available with the online journal). Inconsistent efficacy of ethanol against *S. epidermidis* in our experiments may be due to reduced concentrations of ethanol used in these experiments. Other investigators using higher concentrations of ethanol (>12.5 %) have demonstrated efficacy of ethanol against biofilms composed of *S. aureus* or *Candida parapsilosis*. In conjunction with minocycline and EDTA, ethanol eradicated biofilm growth on catheter discs (Raad *et al.*, 2007a). Chambers *et al.* (2006) reported that ethanol (70 % v/v) was effective against monomicrobial biofilms of *C. albicans*, *Pseudomonas aeruginosa* or *Klebsiella pneumoniae* grown in microtitre plates after exposure to ethanol for 4 h. In early clinical studies, catheter-lock solutions containing 70 % ethanol were effective in preventing or treating catheter infections without adverse effects (Broom *et al.*, 2008; Mouw *et al.*, 2008). These studies indicate that
ethanol holds significant promise as an effective and safe catheter-lock solution.

The chelating agent EDTA significantly reduced biofilm viability of S. epidermidis in polymicrobial biofilms. In monomicrobial biofilms, EDTA was effective against all S. epidermidis and C. albicans strains after 24, 48 and 72 h of exposure (Supplementary Figs S1 and S2 available with the online journal), which is comparable to other reports. Tetrasodium EDTA treatment (40 mg ml⁻¹ for 21 h) significantly reduced the viability of biofilms of S. epidermidis, meticillin-resistant S. aureus, P. aeruginosa, E. coli, K. pneumoniae or C. albicans (Percival et al., 2005). EDTA combined with minocycline has been shown to be effective against biofilms of S. epidermidis, S. aureus and C. albicans in vitro (Raad et al., 2003). The combination of antibiofilm activity and anticoagulant activity makes EDTA a promising candidate for use in catheter-lock solutions against biofilms of common infections.

NAC significantly reduced biofilm viability of S. epidermidis in polymicrobial biofilms at 24 and 48 h. In monomicrobial biofilms, NAC was consistently effective against all strains of S. epidermidis and C. albicans (Supplementary Figs S1 and S2 available with the online journal). NAC (0.007 to 8 mg ml⁻¹) in combination with fosfomycin (128 and 2000 mg ml⁻¹) against four slime-producing uropathogenic E. coli biofilms in vitro and has been shown to reduce EPS and biofilm synthesis (Marchese et al., 2003). Similarly, reduction of EPS (up to 74 %) and biofilm mass (up to 46 %) by NAC (0.003 to 8 mg ml⁻¹) on 15 clinical strains of S. epidermidis biofilms has been reported (Perez-Giraldo et al., 1997).

TLF did not consistently reduce viability of S. epidermidis or C. albicans in either polymicrobial or monomicrobial biofilms (Supplementary Figs S1 and S2 available with the online journal). TLF significantly decreased biomass and mean thickness as assessed by confocal microscopy, which may suggest a static effect rather than a microbicidal effect. Singh et al. (2002) demonstrated that subinhibitory concentrations of lactoferrin (10 to 100 μg ml⁻¹) significantly inhibited the formation of P. aeruginosa biofilms in flow chambers. Leitch & Willcox (1999a) showed that lactoferrin reduced the MIC of vancomycin on biofilms of S. epidermidis formed on artificial contact lenses. Iron sequestration by lactoferrin may be responsible for its antimicrobial effect (Singh, 2004; Valenti & Antonini, 2005). However, TLF on its own may not be an effective catheter-lock solution.

**Evaluation of synergy of the antimicrobial combinations by CIs**

Combinations of antimicrobial agents against biofilms may enhance efficacy, reduce drug dosages and minimize the development of drug resistance. Biofilms are inherently resistant to antibiotics, and antimicrobial combinations may be an important strategy for eradicating biofilm-associated infections. Therefore, we evaluated combinations of NAC, EDTA, ethanol and TLF with antibiotics commonly used in neonatology, by discerning inhibitory end points using the XTT assay, similar to the MBEC₅₀ for single agents. Then, we used the median-effects principle (derived from the mass-action law principle) expounded by Chou and colleague (Chou & Talalay, 1984; Chou, 2006) to evaluate synergy for the antimicrobial combinations. Evaluation of antimicrobial combinations by the
The median-effects method is widely used in cancer and infectious diseases (especially viral diseases) research. The advantages of this method include surmounting the assumption that drug interactions are linear across dosages and drug effects. No general equation fits all the dose–response curves because mechanisms of drug actions differ. Dose–response curves evaluated at various effective doses (from 50 to 90% inhibition) may overcome this problem. Therefore, we evaluated drug combinations in a systematic manner at three different effective doses (ED50, ED75 and ED90) at equipotency or near equipotency ratios of the drug combinations (Martinez-Irujo et al., 1996).

To examine the validity of applying the median effects equation to antimicrobial susceptibilities using both single drugs and combination of drugs, we calculated r, which is the linear coefficient for the goodness of fit of the data to the median effects plot (r = 1 indicates perfect conformity). The mean r value for each isolate of S. epidermidis and C. albicans, including values for single agents and drug combinations, was ≥ 0.95. This value indicates good conformity of the data to the median effects equation and renders our calculation of CIs valid (Chou, 2006).

**Drug combinations with NAC, EDTA, ethanol and TLF indicate synergy**

Against the three strains of S. epidermidis tested (Table 2), EDTA, NAC and ethanol were synergistic with nafcillin and vancomycin (CI < 1) at equipotency or near equipotency ratios at ED50, ED75 and ED90 with no exceptions. TLF was also synergistic with nafcillin and vancomycin (CI < 1) at equipotency drug-dose ratios at ED50, ED75 and ED90 with one exception. TLF was not synergistic when combined in a ratio of 250:1 with vancomycin at ED90 against S. epidermidis S101. CIs for drug combinations against S. epidermidis at constant drug ratios other than equipotency ratios are presented in Supplementary Table S1 (available with the online journal).

Against the two strains of C. albicans tested (Table 3), EDTA and ethanol were synergistic with amphotericin B and fluconazole (CI < 1) at ED50, ED75 and ED90 with no exceptions. NAC was synergistic with amphotericin B and fluconazole (CI < 1) in equipotency drug-dose ratios at ED50, ED75 and ED90 with one exception. NAC was not synergistic when combined with fluconazole in a ratio of 1000:1 at ED90 against the C. albicans strain ATCC MYA 4441. TLF was synergistic with amphotericin B and fluconazole (CI < 1) in equipotency drug-dose ratios at ED50, ED75 and ED90 with one exception. TLF was not synergistic when combined with fluconazole in a ratio of 500:1 (at ED50, ED75 and ED90) against the C. albicans strain ATCC 32354. CIs for drug combinations against C. albicans at constant drug ratios other than equipotency ratios are presented in Supplementary Table S2 (available with the online journal).

The mechanisms for the synergistic effects with antifungal and antistaphylococcal agents are speculative and likely to...

**Table 2. CIs for the drug combinations against S. epidermidis biofilms at equipotency ratios**

CIs were derived by the median effects principle, and indicate synergy if CI < 1, additive effect if CI = 1 and antagonism if CI > 1. The non-synergistic ratio is shown in bold. ED50, ED75, and ED90 represent 50, 75 and 90% inhibitory effects, respectively.

<table>
<thead>
<tr>
<th>S. epidermidis strain</th>
<th>NAF combination ratio</th>
<th>CI values mean (sd)</th>
<th>VAN combination ratio</th>
<th>CI values mean (sd)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ED50</td>
<td>ED75</td>
<td>ED90</td>
<td>ED50</td>
</tr>
<tr>
<td>EDTA:NAF</td>
<td></td>
<td></td>
<td></td>
<td>EDTA:VAN</td>
</tr>
<tr>
<td>ATCC 55133</td>
<td>500:1</td>
<td>0.20 (0.27)</td>
<td>0.16 (0.03)</td>
<td>0.80 (0.44)</td>
</tr>
<tr>
<td>H100</td>
<td>125:1</td>
<td>0.26 (0.07)</td>
<td>0.26 (0.11)</td>
<td>0.26 (0.15)</td>
</tr>
<tr>
<td>S101</td>
<td>125:1</td>
<td>0.18 (0.04)</td>
<td>0.16 (0.04)</td>
<td>0.17 (0.12)</td>
</tr>
<tr>
<td>NAC:NAF</td>
<td></td>
<td></td>
<td></td>
<td>NAC:VAN</td>
</tr>
<tr>
<td>ATCC 55133</td>
<td>1000:1</td>
<td>0.74 (0.39)</td>
<td>0.66 (0.58)</td>
<td>0.64 (0.70)</td>
</tr>
<tr>
<td>H100</td>
<td>125:1</td>
<td>0.16 (0.12)</td>
<td>0.16 (0.18)</td>
<td>0.17 (0.22)</td>
</tr>
<tr>
<td>S101</td>
<td>125:1</td>
<td>0.20 (0.01)</td>
<td>0.30 (0.03)</td>
<td>0.46 (0.10)</td>
</tr>
<tr>
<td>Ethanol:NAF</td>
<td></td>
<td></td>
<td></td>
<td>Ethanol:VAN</td>
</tr>
<tr>
<td>ATCC 55133</td>
<td>25:16</td>
<td>0.45 (0.29)</td>
<td>0.34 (0.19)</td>
<td>0.32 (0.08)</td>
</tr>
<tr>
<td>H100</td>
<td>25:16</td>
<td>0.43 (0.51)</td>
<td>0.24 (0.23)</td>
<td>0.20 (0.14)</td>
</tr>
<tr>
<td>S101</td>
<td>6:16</td>
<td>0.34 (0.24)</td>
<td>0.31 (0.15)</td>
<td>0.37 (0.23)</td>
</tr>
<tr>
<td>TLF:NAF</td>
<td></td>
<td></td>
<td></td>
<td>TLF:VAN</td>
</tr>
<tr>
<td>ATCC 55133</td>
<td>500:1</td>
<td>0.26 (0.08)</td>
<td>0.25 (0.03)</td>
<td>0.27 (0.12)</td>
</tr>
<tr>
<td>H100</td>
<td>1000:1</td>
<td>0.2 (0.05)</td>
<td>0.10 (0.04)</td>
<td>0.07 (0.06)</td>
</tr>
<tr>
<td>S101</td>
<td>250:1</td>
<td>0.23 (0.05)</td>
<td>0.16 (0.05)</td>
<td>0.11 (0.05)</td>
</tr>
</tbody>
</table>

NAF, Nafcillin; VAN, vancomycin.

*Indicates ratios close to equipotency ratios.
Table 3. CIs for the drug combinations against *C. albicans* biofilms at equipotency ratios

CIs were derived by the median effects principle, and indicates synergy if CI < 1, additive effect if CI = 1 and antagonism if CI > 1. Non-synergistic combinations are shown in bold. ED_{50}, ED_{75}, and ED_{90} represent 50, 75 and 90% inhibitory effects, respectively.

<table>
<thead>
<tr>
<th><em>C. albicans</em> strain</th>
<th>AMB combination ratio</th>
<th>CI values mean (sd)</th>
<th>FLC combination ratio</th>
<th>CI values mean (sd)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EDTA:AMB</td>
<td>ED_{50}</td>
<td>ED_{75}</td>
<td>ED_{90}</td>
</tr>
<tr>
<td>ATCC 32354</td>
<td>500:1</td>
<td>0.14 (0.12)</td>
<td>0.11 (0.04)</td>
<td>0.10 (0.02)</td>
</tr>
<tr>
<td>ATCC MYA 4441</td>
<td>500:1</td>
<td>0.07 (0.01)</td>
<td>0.03 (0.01)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>NAC:AMB</td>
<td>500:1</td>
<td>0.04 (0.02)</td>
<td>0.02 (0.01)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td>ATCC 32354</td>
<td>1000:1</td>
<td>0.17 (0.09)</td>
<td>0.09 (0.01)</td>
<td>0.06 (0.04)</td>
</tr>
<tr>
<td>ATCC MYA 4441</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol:AMB</td>
<td>12.5:1*</td>
<td>0.51 (0.29)</td>
<td>0.40 (0.21)</td>
<td>0.37 (0.21)</td>
</tr>
<tr>
<td>ATCC 32354</td>
<td>12.5:1†</td>
<td>0.67 (0.36)</td>
<td>0.61 (0.11)</td>
<td>0.39 (0.15)</td>
</tr>
<tr>
<td>ATCC MYA 4441</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLF:AMB</td>
<td>500:1</td>
<td>0.19 (0.02)</td>
<td>0.34 (0.33)</td>
<td>0.16 (0.07)</td>
</tr>
<tr>
<td>ATCC 32354</td>
<td>2000:1</td>
<td>0.11 (0.04)</td>
<td>0.06 (0.03)</td>
<td>0.04 (0.03)</td>
</tr>
</tbody>
</table>

AMB, Amphotericin B; FLC, fluconazole.

*Ratios not at equipotency but combinations of MBEC_{50} of ethanol with 1/64th or 1/32nd MBEC_{50} concentrations of amphotericin B and fluconazole, respectively.

†Ratios not at equipotency but combinations of MBEC_{50} of ethanol with 1/64th or 1/32nd MBEC_{50} concentrations of amphotericin B and fluconazole, respectively.

vary with the different agents. EDTA is a divalent cation (calcium and magnesium) chelator and may have inhibitory effects against *Candida* and *Staphylococcus* strains (Gordon *et al.*, 1991; Ozerdem Akpolat *et al.*, 2003; Percival *et al.*, 2005; Ramage *et al.*, 2007; Root *et al.*, 1988). NAC and ethanol may act by inhibiting the production of EPS or facilitating its degradation (Alem & Douglas, 2005; Gastaldo *et al.*, 1994; Xu *et al.*, 1999). The synergistic effects of lactoferrin may be due to iron sequestering effects or a direct lytic effect on the cell membranes of *Candida* and *Staphylococcus* (Leitch & Willcox, 1999b; Xu *et al.*, 1999). We have reported the synergistic effects of human recombinant lactoferrin on planktonic cells of clinical isolates of *S. epidermidis* and *C. albicans* (Venkatesh & Liang, 2008). We speculate that the action of lactoferrin on cell membranes complements the action of other drugs.

The key observations of this study are that EDTA, NAC, ethanol and TLF decreased the biomass and thickness of *S. epidermidis* and *C. albicans* biofilms. EDTA, NAC and ethanol consistently reduced viability in monomicrobial biofilms. Ethanol (12.5 %, MBEC_{50}) was the only agent that reduced viability of *C. albicans* in polymicrobial biofilms. Ethanol at higher concentrations (25 to 70 %) has been found to be effective against biofilms in other studies (Chambers *et al.*, 2006; Raad *et al.*, 2007a). NAC, EDTA, ethanol and TLF were synergistic with antibacterial and antifungal antibiotics against biofilms of *S. epidermidis* and...
C. albicans. Polymicrobial infections account for approximately half of all paediatric CRBSIs resulting from catheter biofilms. Candida (approximately 10%) and Gram-positive organisms (mostly staphylococci, approximately 10%) are other major causes of paediatric CRBSIs (Almuneef et al., 2006). Precious vascular indwelling catheters are removed after refractory C. albicans CRBSI and S. epidermidis CRBSIs. Our results suggest that NAC, EDTA or ethanol alone or in combination with antibiotics used as catheter-lock solutions for 24 to 72 h may eradicate infections due to S. epidermidis and C. albicans and help in the retention of vascular catheters. We conclude that catheter-lock solutions utilizing NAC, EDTA and ethanol individually or in combination with antibiotics might be used to salvage infected catheters, and will directly impact patient morbidity and health-care costs.

ACKNOWLEDGEMENTS

We acknowledge the help of Agennix Inc. for donating recombinant human lactoferrin (TLF) for our research. We thank Claus Sternberg PhD, BioSys-DTU, Denmark, for the COMSTAT 2 software used in the analyses of confocal images of biofilms. We thank Barbara Trautner MD, VA Center, Houston, TX (for confocal imaging of biofilms), Sara Jones PhD and members of J. Versalovic’s lab for insightful discussions.

REFERENCES


by the novel computer program COMSTAT. Microbiology 146, 2395–2407.


