Synergistic effect of fennel essential oil and hydrogen peroxide on bacterial biofilm

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Abstract

Introduction: Staphylococcal biofilm formation significantly challenges wound management. The causes of difficult-to-treat wounds are not only methicillin-resistant staphylococci, but also methicillin-sensitive strains with different patterns of resistance. Bacterial biofilm significantly limits the access and activity of antimicrobials used in dermatological infections.

Aim: To evaluate the synergistic effect of fennel essential oil (FEO) and H2O2 on biofilm formation by Staphylococcus aureus (MSSA and MRSA) reference strains.

Material and methods: Minimum inhibitory concentration (MIC) values were determined for FEO and H2O2 against S. aureus reference strains by the broth microdilution method. The combined effects of the FEO and H2O2 were calculated and expressed in terms of a fractional inhibitory concentration index (FICI) using the checkerboard method. The FEO composition was analyzed by the GC-MS method. The data were analysed by one-way ANOVA.

Results: Decreased MIC values for FEO combined with H2O2 were observed in comparison to FEO itself. The combinations of FEO and H2O2 determined synergistic effects on all S. aureus reference strains. Subinhibitory concentration of FEO alone and in combination with 0.5 MIC of H2O2 significantly decreased the production of biofilm biomass in S. aureus strains and reduced the metabolic activity of attached cells.

Conclusions: Combination of fennel essential oil containing nearly 80% trans-anethole and H2O2 represents a potential for further basic and applied research on wound management.

Key words: Staphylococcus aureus, biofilm, fennel essential oil, H2O2

Introduction

Biofilm formation is one of the most important factors influencing wound infections and may result in biofilm-related sepsis, which is the major cause of wound-related mortality. Organized bacterial biofilm communities enhance antibiotic resistance, complicate the treatment and result in development of chronic infection [1–4]. Literature data indicate that approximately three-fourths of deaths among burned patients occur due to wound bacterial infections, mostly with Staphylococcus aureus, Staphylococcus epidermidis, Escherichia coli, and Pseudomonas aeruginosa [1, 5]. These bacteria are able to produce biofilm, which protects them against the host immune system as well as antibiotic therapy.

Staphylococcus aureus is frequently isolated from patients with therapeutically challenging wound infections [6]. Moreover, infections with methicillin-resistant S. aureus strains (MRSA) which additionally produce biofilm are recognized as extremely hard to mediate. Stress conditions such as antibiotics, sodium chloride, temperature, and oxidative stress can induce biofilm formation by S. aureus [7]. Yin et al. suggest that serum of a burned patient increases the biofilm formation by S. aureus via the induction of oxidative stress [8].

In recent decades there has been growing interest in activity of plant metabolites. This is due to the development of disciplines such as biochemistry, phytochemistry, pharmacology and genetics. One of the biggest plant families on earth is named the Apiaceae family and rep...
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Material and methods

Strains and culture conditions

Three reference strains were used in this study: S. aureus ATCC 29213 (methicillin-sensitive S. aureus – MSSA), S. aureus ATCC 43300 (MRSA) and S. aureus ATCC 6538 (MSSA) as a reference biofilm forming strain [14]. The bacteria were cultivated for 18 h at 37°C on Columbia agar with 5% sheep blood (bioMérieux, Warsaw, Poland).

Determining antimicrobial activity of the essential oil

The checkerboard method was performed according to Yap et al. [18] with minor modifications: the final concentration of bacterial suspension was 10⁶ CFU/ml and resazurin was added to each plate well after 18 h of incubation. To determine MICs for individual mixtures of both compounds, serial dilutions of FEO (250 µl/ml – 0.12 µl/ml) and H₂O₂ (40 – 0.04 mM) were combined in 96-well polystyrene microtiter plates. Each well contained: 25 µl of the appropriate concentration of FEO, 25 µl of the appropriate concentration of H₂O₂, and 50 µl of bacterial suspension containing a final concentration of 10⁶ CFU/ml in each well. The plates were incubated at 35°C for 18 h. All determinations were performed in duplicate. The MICs of both FEO and H₂O₂ in combination and alone were determined as described above. The combined effects of the FEO and H₂O₂ were calculated and expressed in terms of a fractional inhibitory concentration index (FICI) using the following formula: FICI = MIC of FEO or H₂O₂ in combination/MIC of FEO or H₂O₂. Results were interpreted as synergy (FICI ≤ 0.5), no interaction (FICI > 0.5–4.0) or antagonism (FICI > 4.0) [18].

Biofilm formation and assessment of essential oil biofilm formation prevention

Biofilm formation assay was performed according to Latimer et al. [19] with minor modifications. Overnight cultures of S. aureus ATCC 6538 were diluted 1:200 with lysogeny broth (LB) medium (Sigma-Aldrich, Darmstadt, Germany) and aliquots of 200 µl were transferred to

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96-well polystyrene microtiter plates and incubated stationary at 37°C for 24 h. In order to evaluate the prevention of biofilm formation, FEO was added in 0.5 MIC and 0.25 MIC concentrations. Determination of the H₂O₂ effect on biofilm formation was performed by the addition of 0.5 MIC of H₂O₂ to a cell suspension which contained 0.5 and 0.25 MIC concentration of FEO. After incubation, wells were emptied and washed five times with PBS to remove planktonic and unattached cells.

The cell viability and biofilm mass were measured in the resazurin assay and crystal violet staining according to Skogman et al. [20] with minor modifications. FEO treated wells containing *S. aureus* biofilm were filled with 200 µl of fresh LB containing 20 mM of resazurin (Sigma-Aldrich, Darmstadt, Germany) and incubated for 20 min at 37°C with shaking (200 rpm). After the incubation, medium was removed and fluorescence (λ<sub>ex</sub> = 520 nm; λ<sub>em</sub> = 590 nm) was measured. Wells were washed three times using PBS buffer (Sigma-Aldrich, Darmstadt, Germany) for the biomass quantification. At this stage, 200 µl of methanol (Sigma-Aldrich, Darmstadt, Germany) was added to each well for fixation and incubated for 20 min. Afterwards, methanol was removed, and plates were air dried. Staining was performed with 200 µl of crystal violet (1% w/v, Sigma-Aldrich, Darmstadt, Germany) added to wells and further incubated for 20 min at room temperature. Pigment was rinsed with sterile water. 200 µl of ethanol: acetone (8 : 2, v/v) solution was added to each well and biofilm was quantified by determining the optical density at 590 nm.

The influence of FEO and combination of FEO with H₂O₂ on *S. aureus* biofilm formation was calculated as a % of formed biofilm compared to the control. The control for the influence of FEO was a biofilm formation assay with Tween 80. For combination of FEO and hydrogen peroxide the 0.5 MIC of H₂O₂ with Tween 80 was used as a control.

**Statistical analysis**

The obtained data were analysed by one-way ANOVA. *P*-values below 0.05 were considered as statistically significant. All statistical analyses were performed using GraphPad Prism 5.02 (Graph Pad Software, San Diego, CA).

### Results

**Chemical analysis of FEO**

The GC-MS analysis enabled identification of eleven compounds. The main constituent of FEO was trans-anethole (77.9%) followed by fenchone (12.8%), α-pinene (3.8%), estragole (2.3%) and limonene (2.1%) [15].

| *Staphylococcus aureus* strain | MIC of FEO [mg/ml] | MIC of H₂O₂ [mM] | FIC FEO | FIC H₂O₂ | FICI | Type of interaction |
|-------------------------------|-------------------|-----------------|--------|---------|-----|--------------------|
| ATCC 6538                     | 7.1 ± 1.2         | 1.5 ± 0.2       | 0.02   | 0.46    | 0.48 | Synergistic        |
| ATCC 43300                    | 6.0 ± 0.0         | 1.2 ± 0.0       | 0.01   | 0.42    | 0.43 | Synergistic        |
| ATCC 29213                    | 10.0 ± 3.4        | 2.1 ± 0.7       | 0.03   | 0.47    | 0.50 | Synergistic        |

**Figure 1.** Effect of subinhibitory concentration of fennel essential oil (FEO) (A) and subinhibitory concentration of FEO in combination with 0.5 MIC of H₂O₂ (B) on process of biofilm biomass and metabolic activity formation.
Antistaphylococcal inhibitory activity of FEO and H$_2$O$_2$

The results revealed that all *S. aureus* reference strains were susceptible to FEO and H$_2$O$_2$. The highest activity of FEO and H$_2$O$_2$ was determined. The combinations of FEO and H$_2$O$_2$ showed synergistic effects (FICI = 0.43–0.5) on all *S. aureus* reference strains. It was observed that the most effective combination of FEO and H$_2$O$_2$ decreased the MIC of FEO from 75.9 ±21.5 mg/ml to 0.12 mg/ml. Moreover, it was also noted that the addition of 1% Tween 80 had no impact on the growth of reference strains. The results of MICs and checkerboard assay against *S. aureus* reference strains are summarized in Table 1.

Biofilm formation

Results presented in Figure 1 A showed that subinhibitory concentrations (0.5 MIC and 0.25 MIC) of FEO significantly decreased the production of biofilm biomass in *S. aureus* strains and reduced the metabolic activity of attached cells. Statistically significant (p < 0.001) differences were observed for all analysed strains when the FEO-treated group was compared to the control. Moreover, the addition of H$_2$O$_2$ (Figure 1 B) resulted in statistically significant reduction of biofilm biomass compared to the control (p < 0.001) and 0.5 MIC FEO-only treated cells (p < 0.05).

The results also showed that used 1% Tween 80 concentration decreased the level of *S. aureus* biofilm formation to 89.56% compared to the control without Tween 80. Additionally, the concentration of H$_2$O$_2$ used increased the biofilm formation level to 116.78% compared to the control.

Discussion

Infections represent the major challenge in the management of wounds. In clinical practice, burn wounds are particularly difficult to heal. Furthermore, due to the protein imbalance accompanying a severe burn-related condition, burn wounded patients are recognized as extremely highly susceptible to systemic infections and require specialized intensive care. Therefore, antimicrobial agents represent a significant tool in the intensive care of burn wounds, which additionally act as an infection gate. Hence there is an emerging need for safe and efficient antiseptics dedicated to topical application at different stages of wound healing. Topical antiseptics appear more beneficial compared to systemic antibiotics as they do not generate the emergence of multidrug resistance, represent a broader antimicrobial spectrum and additionally are less likely to provoke allergic reactions. Several well-known basic ones are used to decontaminate the wounds, including H$_2$O$_2$, acetic acid, iodine, chlorhexidine, silver sulfadiazine and silver nitrate. A number of studies have shown both their advantages and disadvantages, but the majority of clinical trials confirmed their safety and lack of a negative influence on wound healing [21]. Recently, many scientific centres have conducted research on synergistic or additive action of antiseptic agents. Current literature presents data on an increased activity of H$_2$O$_2$ combined with chlorhexidine against *Streptococcus sobrinus*, *Enterococcus faecalis* and *S. aureus* in oral infections [22, 23]. H$_2$O$_2$ also presents synergistic as well as additive activity with iodine against other Gram-positive and Gram-negative bacteria and yeast [24]. Other authors reported that H$_2$O$_2$ in combination with alcohols at concentrations of 3% and 5% rapidly eradicates *S. epidermidis* biofilms from surfaces of implant materials [25]. Grønseth et al. showed also the antibacterial efficacy of Lugol's solution, acetic acid, and boric acid against *S. aureus* biofilm [26]. They found high effectiveness of Lugol's solution against biofilm consisting of *S. aureus* clinical strains. Another study confirmed the anti-biofilm potential of essential oils and their major components as well [27]. H$_2$O$_2$ is still a commonly used and cheap agent for wound decontamination. Regarding this we decided to investigate the possible prevention of *S. aureus* biofilm formation by H$_2$O$_2$ combined with FEO. The GC-MS analysis of FEO showed that its composition was consistent with the European Pharmacopoeia recommendations [28]. Our previous study showed that the FEO possesses strong antistaphylococcal activity and increases the antimicrobial activity of cefoxitin, mupirocin, co-trimoxazole and ciprofloxacin [15]. Our current study found that the combination of FEO and H$_2$O$_2$ reveals a synergistic effect against reference strains: *S. aureus* ATCC 6538, *S. aureus* ATCC 43300 and *S. aureus* ATCC 29213. Furthermore, we proved that subinhibitory concentrations 0.5 and 0.25 MIC of FEO successfully decrease the production of biofilm biomass and reduce the metabolic activity of attached cells. Moreover, our studies confirmed that 1% Tween 80 concentration decreased the level of *S. aureus* biofilm formation, in contrast to H$_2$O$_2$, which increased its formation. These results correspond with published data of Toutain-Kidd et al. and Kulkarni et al. [29, 30]. It is known that the etiological factors of wound infections are not only bacterial pathogens, but also fungi such as yeast and dermatophytes. Essential oils of plants from the Apiaceae family also have antifungal activity *inter alia* against *Candida* spp., *Trichophyton* spp. and *Microsporum* spp. [31].

Conclusions

Our studies indicated that FEO containing mainly *trans*-anethole have a great potential for biofilm prevention. Moreover, these results will encourage for further research in order to determine the balanced level of activity dependently on the exposure time and anti-biofilm mechanism of FEO with H$_2$O$_2$. Because of the low toxic-
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ity of fennel essential oil and also the main constituent, trans-anethole, they can be a valuable addition to preparations used in challenging wound infections caused by MSSA and MRSA isolates.

Conflict of interest

The authors declare no conflict of interest.

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