Research Article
Exogenous Pulmonary Surfactant as a Vehicle for Antimicrobials: Assessment of Surfactant-Antibacterial Interactions In Vitro

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Owing to its unique surface-active properties, an exogenous pulmonary surfactant may become a promising drug delivery agent, in particular, acting as a vehicle for antibiotics in topical treatment of pneumonia. The purpose of this study was to assess a mutual influence of natural surfactant preparation and three antibiotics (amikacin, cefepime, and colistimethate sodium) in vitro and to identify appropriate combination(s) for subsequent in vivo investigations of experimental surfactant/antibiotic mixtures.

Influence of antibiotics on surface-active properties of exogenous surfactant was assessed using the modified Pattle method. Effects of exogenous surfactant on antibacterial activity of antimicrobials against Staphylococcus aureus, Klebsiella pneumoniae, and Pseudomonas aeruginosa were evaluated using conventional microbiologic procedures. Addition of amikacin or cefepime to surfactant had no significant influence on surface-active properties of the latter. Obvious reduction of surface-active properties was confirmed for surfactant/colistimethate composition. When suspended with antibiotics, surfactant either had no impact on their antimicrobial activity (amikacin) or exerted mild to moderate influence (reduction of cefepime bactericidal activity and increase of colistimethate bacteriostatic activity against S. aureus and P. aeruginosa). Considering favorable compatibility profile, the surfactant/amikacin combination is advisable for subsequent investigation of joint surfactant/antibacterial therapy in animals with bacterial pneumonia.

1. Introduction
The success of pneumonia treatment in large part is defined by effectiveness of antimicrobial therapy. In turn, efficiency of antibacterial therapy depends on formation of sufficient antimicrobial drug concentration in the site of infection [1]. Direct administration of antibiotics into a tracheobronchial tree using nebulization or intratracheal instillations can provide high concentration of drug in a focus of infection with low level of systemic absorption and, therefore, decreased systemic toxicity [2]. However, in patients with pulmonary diseases directly administered drug may predominantly accumulate in central rather than in peripheral airways. This negative effect is attributable to physiologic properties of fluid distribution in respiratory pathways and to specific inflammatory alterations such as bronchial hypersecretion, bronchoconstriction, and bronchial edema [3–5].

It was hypothesized that use of exogenous pulmonary surfactant as a vehicle for antibacterial agents could enhance the efficiency of local antimicrobial therapy in pneumonia [6, 7]. Pulmonary surfactant is a lipoprotein complex produced by cells of respiratory tissue that ensures a variety of essential physiologic functions [8]. One of the most important features of surfactant is the ability to decrease a surface tension, thus providing normal alveolar ventilation and gas exchange and preventing alveolar collapse [9]. It has been shown that, owing to its specific composition, an exogenous surfactant promotes effective and uniform peripheral distribution of fluid in lungs [6]. Furthermore, given the fact that exogenous pulmonary surfactant is able to reexpand atelectatic areas, it is anticipated that, after local administration with surfactant, antimicrobials will deposit in effective concentrations even in collapsed areas of lungs which are more likely to be infected [5].
2. Materials and Methods

2.1. Surfactant and Antibiotics. Sterile natural pulmonary surfactant preparation (Suzacrin, Docpharm, Ukraine) was used. This emulsion includes purified phospholipids (76%; 50 mg per 1 mL of emulsion) isolated from porcine lung homogenates and physiological solution as an excipient. Suzacrin contains surfactant-associated proteins B and C but is free of surfactant-proteins A and D.

The following antibiotics were utilized: amikacin (Amilc, Kievmedpreparat, Ukraine), cefepime (Cefepime, Nectar Lifesciences Ltd., India), and colistimethate sodium (Colomycin Injection, Forest Laboratories UK Ltd., UK). These antibacterial agents are currently recommended to treat pulmonary infections, caused by multidrug-resistant pathogens.

Solutions of antibiotics, emulsion of surfactant, and experimental mixtures of antibiotics in surfactant were freshly prepared in aseptic conditions using sterile 0.9% NaCl solution immediately before testing.

Specific requirements were established to standardize experiments and to provide a balanced calculation of antibiotic and surfactant amount in experimental mixtures: quantitative ratio of antibiotic and surfactant should correspond to the ratio of mean daily doses recommended for adult male patient with a body mass of 70 kg, that is, surfactant phospholipids—700 mg, cefepime—2,000 mg, amikacin—1,000 mg, and colistimethate sodium—4,000,000 IU (320 mg).

2.2. Test Strains and Culture Media. The following test strains were provided by Crimean Sanitary-Epidemiological Station (Simferopol, Ukraine): Staphylococcus aureus ATCC25923, Klebsiella pneumoniae 3534/51, and Pseudomonas aeruginosa ATCC27853. Hottinger broth (Federal State Institution of Science “State Research Center of Applied Microbiology and Biotechnology,” Obolensk, Russia; amine nitrogen concentration—132 mg%) and meat-peptone agar (MPA; State Pilot Factory of Bacterial Cultures of the Institute of Milk and Meat Technology, Kiev, Ukraine; amine nitrogen concentration—2.7 mg%) were used as culture media to investigate susceptibility of bacteria to antibiotics, surfactant, and surfactant-antimicrobial mixtures.

2.3. Assessment of Surface-Active Properties. The commercial surfactant preparation was diluted (reemulsified) in sterile 0.9% NaCl solution (control) or similar volume of antibiotic solution (three test series) to produce equal final phospholipid concentration of 20.6 mg/mL. The total volume of prepared experimental mixtures was 34 mL (a volume allowable for intratracheal administration to adult person within 24 hours). Final concentrations of antibiotics in surfactant-containing mixtures were as follows: amikacin—29.4 mg/mL, colistimethate sodium—117,647 IU/mL, and cefepime—58.8 mg/mL.

Apart from the experimental series, five subsidiary series were investigated: undiluted surfactant preparation (phospholipid concentration—50 mg/mL), solutions of amikacin, colistimethate sodium, and cefepime in concentrations recommended for clinical use (167 mg/mL, 500,000 IU/mL and 100 mg/mL, resp.), and diluent (0.9% NaCl solution).

The experiment was conducted at a temperature of 26°C. Test suspensions, as well as control and subsidiary samples (five samples for every series), were foamed in sterile tubes with single-use medical syringes equipped with 23G injection needles. Foam was formed by triple aspiration and return of test material into a tube. The modified Pattle method [14, 15] was utilized to assess surface-active properties in stable foam. This method enables an evaluation of surface tension force dynamics on a liquid-gas interphase boundary according to the changes of air bubble diameter. For this purpose, hanging drops of obtained foam were examined in transmitted light using Olympus CX41 microscope equipped with Olympus C5050Z digital camera. One field of vision (200× magnification) uniformly filled with bubbles was photographed in every drop in automatic mode during 20 min with an interval of 30 sec. Thereby, each replication in a series included 41 shots (205 shots for each series composed of 5 replications). Obtained images (a total of 1,230 images) were analyzed using Olympus DP-Soft 3.11 application. Changes of 20 randomly chosen bubbles were monitored through all images of every replication. Bubble diameter (μm) was measured for the first and final (obtained after 20 min) images only. Totally, 1,200 bubble measurements were performed during this experiment. Stability index (SI) was calculated for each replication using the formula

\[ SI = \frac{\sum d_x^2}{\sum d_y^2}, \]  

where \( d_x \) is a result of final measurement in a series (41st image) and \( d_y \) is a result of first measurement (1st image).

2.4. Susceptibility Testing. Minimum inhibitory concentrations (MIC) of test substances were determined using conventional technique of serial dilution in Hottinger broth.
2.5. Statistics. Most data are presented as a mean ± standard error. Data were compared using the unpaired Student’s t-test. A probability level of $P < 0.05$ was considered to be statistically significant. Statistical analysis was performed using STATISTICA software version 10.0 (Stat Soft Inc., Tulsa, OK, USA).

### 3. Results

#### 3.1. Assessment of Surface-Active Properties. The assessment of foaming properties of the official surfactant preparation, antibiotics (in therapeutic concentrations), and solvent demonstrated a wide range of surface activity characteristics (Table 1): from almost complete absence of foaming ability in normal saline to the formation of stable foam (which persisted ≥20 min) in surfactant and colistimethate. Foaming properties of amikacin and cefepime solutions were rated as intermediate, but close to normal saline.

Bubbles of colistimethate sodium solution were significantly larger than bubbles of surfactant suspension both in the beginning ($P < 0.001$) and at the end of the experiment ($P < 0.001$). The diameter of colistimethate sodium and surfactant bubbles decreased during the experiment by 21% and 8%, respectively ($P < 0.001$). SI values also suggested significantly higher surface activity of surfactant as compared with colistimethate sodium ($P < 0.001$).

Comparison of surfactant properties before and after dilution with normal saline (Tables 1 and 2) showed that 2.4-fold decrease of phospholipid concentration (20.6 mg/mL versus initial 50 mg/mL) does not result in significant changes of surface activity as per SI value ($P > 0.05$). However, the diameter of bubbles of diluted surfactant was significantly higher as compared with diameter of original surfactant suspension bubbles both in the beginning and at the end of the experiment ($P < 0.001$), thus suggesting a trend for reduction of surface activity.

As compared with control, experimental surfactant/amikacin mixture demonstrated smaller diameter of bubbles (Table 2) both in the beginning and at the end of the experiment ($P < 0.001$), as well as significantly lower tendency for reduction of bubble size in 20 min ($P < 0.001$), whereas there were no substantial changes of SI ($P > 0.05$).

The surfactant/cefepime mixture also retained high surface activity as per SI values ($P > 0.05$). However, this mixture differed from the control by greater bubble diameter in the beginning of the experiment ($P < 0.01$) and somewhat more pronounced, or accelerated, reduction of bubble size ($P < 0.01$).

| Table 1: Foaming properties and stability index values for original preparations. |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Foam properties                          | Surfactant suspension             | Colistimethate sodium solution               | Amikacin solution                             | Cefepime solution                             | NaCl solution                                |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Diameter of bubbles, M ± m (μm)             | Stable, >20 min                        | Stable, >20 min                              | Unstable, 5–7 sec                             | Unstable, 10–15 sec                           | No foam                                      |
| (a) start of experiment                      | 51.55 ± 1.06 (100)                     | 110.62 ± 1.65 (100)                          | —                                             | —                                             | —                                            |
| (b) end of experiment                        | 47.46 ± 0.94 (100)                      | 87.54 ± 2.27 (100)                           | —                                             | —                                             | —                                            |
| Difference between (a) and (b)              | 4.09 ± 0.29 (100)                      | 23.07 ± 1.58 (100)                           | —                                             | —                                             | —                                            |
| Stability index (SI)                         | 0.85 ± 0.02 (5)                        | 0.65 ± 0.03 (5)                              | —                                             | —                                             | —                                            |

Note: M ± m: mean ± standard error.
P. aeruginosa when tested against colistimethate sodium (\(P<0.05\)) of bacterial strains. This antibiotic completely inhibited growth. The exogenous surfactant preparation—MIC and MBC data (mg/L)

| Antibiotics and antibiotic/surfactant compositions | S. aureus | K. pneumoniae | P. aeruginosa |
|--------------------------------------------------|-----------|--------------|--------------|
| Amikacin                                         | 3.9       | 1.9          | 3.9          |
| Amikacin + surfactant                             | \(\leq0.49\) | 1.9          | 3.9          |
| Cefepime                                         | \(\leq0.49\) | \(>1,000\)  | 3.9          |
| Cefepime + surfactant                             | 3.9       | \(>1,000\)  | 1,000        |
| Colistimethate sodium                             | 80        | 20           | 20           |
| Colistimethate sodium + surfactant                | 80        | 20 (10)      | 10           |

Note: MBC: minimum bactericidal concentration; MIC: minimum inhibitory concentration. Additional MIC values are presented in round parentheses when different results were obtained for distinct replications.

3.2. Susceptibility Testing. The exogenous surfactant preparation was devoid of apparent intrinsic antimicrobial effects as for S. aureus, K. pneumoniae, and P. aeruginosa cultures.

Amikacin demonstrated its efficiency against all three bacterial strains. This antibiotic completely inhibited growth of S. aureus and P. aeruginosa in 256-fold dilution, as well as growth of K. pneumoniae—in 526-fold dilution, that is, in concentration of 3.9 and 1.9 mg/L, respectively (Table 3). Antibacterial properties of amikacin were not affected when combined with surfactant suspension—MIC and MBC remained on the same level.

Cefepime exhibited most pronounced antistaphylococcal activity (MIC \(\leq 0.49\) mg/L; MBC = 1.9 mg/L). However, when tested against P. aeruginosa, MBC of cefepime was significantly (128-fold) higher than MBC of amikacin, whereas antipseudomonal MICs of these antibiotics were equally substantial. K. pneumoniae demonstrated full resistance to cefepime (bacterial growth was observed in all dilutions both in broth and after reinoculation on agar). Suspending of exogenous surfactant in cefepime resulted in slight decrease of bactericidal activity against S. aureus and P. aeruginosa cultures.

Colistimethate sodium had significantly lower antibacterial activity as compared to amikacin (against all three cultures) and cefepime (against S. aureus). The ability of colistimethate sodium to inhibit growth of K. pneumoniae and P. aeruginosa was moderate but higher than in cefepime. When combined with surfactant, bacteriostatic effect of colistimethate increased 4- and 2-fold for S. aureus and P. aeruginosa, respectively, though remaining on relatively low level (20 mg/L and 10 mg/L), while bactericidal activity was unchanged.

4. Discussion and Conclusions

It has been previously shown that interactions between antibiotics and surfactant may exist, and these interactions may influence efficiency of either substances [7, 10]. The purpose of this study was to assess potential mutual influence of natural surfactant preparation and three antibiotics (amikacin, cefepime, and colistimethate sodium) \(in vitro\) and to identify appropriate combination(s) for subsequent investigations of topical surfactant/antibiotic therapy in experimental acute bacterial pulmonary infection. Potential limitations of this study include restrictions as regards extrapolation of the results to other exogenous surfactant preparations due to differences in chemical composition of currently available surfactant products.

In the first part of the study it has been revealed that addition of the amikacin or cefepime to the surfactant had no significant influence on the surface-active properties.
of the latter, whereas obvious reduction of this feature was detected when mixing surfactant with colistimethate sodium. Considering the ability of colistimethate sodium to disrupt phospholipid bilayer of bacterial cell envelope [16], supposedly the observed effect may be caused by specific interaction of the colistimethate sodium with phospholipids of the surfactant.

The results of microbiological part of the study suggest that the surfactant preparation was devoid of intrinsic antibacterial activity. When mixed with antibiotics, the surfactant either had no impact on antimicrobial activity of the latter (e.g., amikacin entirely preserved its properties) or exerted mild to moderate influence. Specifically, there was a trend for decrease of cefepime bactericidal activity and increase of colistimethate sodium bacteriostatic activity against S. aureus and P. aeruginosa.

Interaction between exogenous surfactant and antibiotics was previously studied by van’t Veen et al. [7, 10]. They have determined that surface-active properties of bovine pulmonary surfactant were not altered after addition of ceftazidime or pentamidine, whereas activity of surfactant was depressed with amphotericin B and amoxicillin. Surfactant surface-active properties in tobramycin/surfactant mixture were dependent on the type of solvent used. Surface-active properties of the surfactant were depressed when saline was utilized as a solvent but unaffected when tobramycin was mixed with surfactant in 0.2 M NaHCO₃ buffer [10].

An ability of exogenous surfactant to suppress activity of certain antibiotics was demonstrated in vitro [7] in terms of tobramycin, whereas bactericidal activity of amoxicillin and ceftazidime was not altered. The authors have explained the depression of tobramycin antibacterial activity against K. pneumoniae, P. aeruginosa, S. aureus, and Streptococcus pneumoniae by the ability of aminoglycosides to bind negatively charged phospholipids contained in surfactant preparation and assumed that an excess of phospholipids can inactivate almost all the aminoglycosides [5, 7].

In contrast to the aforesaid tobramycin/surfactant compatibility issues [7, 10], the results of present study indicate that activity of amikacin (another aminoglycoside antibiotic) was not suppressed by the surfactant preparation, and surface-active properties of the surfactant appeared unaffected when saline was used as a solvent for antibiotic, suggesting that not all aminoglycosides possess negative interaction with exogenous surfactant, at least considering specific features of given experiments (different surfactant preparation, different concentration of surfactant in the mixture, etc.).

Assuming relatively low activity of the colistimethate sodium against tested bacterial cultures, as well as noticeable reduction of surfactant surface activity in the surfactant/colistimethate sodium mixture, the use of this composition in subsequent studies in animals infected with S. aureus, K. pneumoniae, and P. aeruginosa appears to be unreasonable. Conversely, it is advisable to use the surfactant/amikacin composition for experimental studies in animals infected with given strains of S. aureus, K. pneumoniae, and P. aeruginosa, and the surfactant/cefepime composition for experimental staphylococcal infection in laboratory animals.

In summary, the study showed that an addition of therapeutic concentrations of the amikacin and cefepime to the exogenous surfactant preparation does not cause a decrease of surfactant surface activity in vitro, whereas significant suppression of both surfactant and colistimethate sodium surface-active properties is evident when mixed in one volume. Addition of the surfactant suspension to amikacin had no influence on high antimicrobial activity of the latter, whereas suspending surfactant with cefepime or colistimethate sodium resulted in a trend for decrease of cefepime bactericidal activity and increase of colistimethate sodium bacteriostatic activity against S. aureus and P. aeruginosa. Obtained data confirm the necessity of surfactant/antibacterial interaction assessment before utilization of any surfactant/antibiotic mixtures in clinical settings and in preclinical animal studies and show that further investigation of combined surfactant/antibacterial therapy should include an evaluation of the surfactant/amikacin composition in animals with bacterial pneumonia.

Conflict of Interests

The author, Alexei Birkun, declares that there is no conflict of interests regarding the publication of this paper.

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