



Encapsulation in fusogenic liposomes broadens the spectrum of action of vancomycin against Gram-negative bacteria

Daria Nicolosi, Marina Scalia, Vito M. Nicolosi, Rosario Pignatello

► To cite this version:

Daria Nicolosi, Marina Scalia, Vito M. Nicolosi, Rosario Pignatello. Encapsulation in fusogenic liposomes broadens the spectrum of action of vancomycin against Gram-negative bacteria. *International Journal of Antimicrobial Agents*, 2010, 35 (6), pp.553. <10.1016/j.ijantimicag.2010.01.015>. <hal-00585818>

HAL Id: hal-00585818

<https://hal.science/hal-00585818v1>

Submitted on 14 Apr 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Accepted Manuscript

Title: Encapsulation in fusogenic liposomes broadens the spectrum of action of vancomycin against Gram-negative bacteria

Authors: Daria Nicolosi, Marina Scalia, Vito M. Nicolosi, Rosario Pignatello



PII: S0924-8579(10)00060-9
DOI: doi:10.1016/j.ijantimicag.2010.01.015
Reference: ANTAGE 3239

To appear in: *International Journal of Antimicrobial Agents*

Received date: 29-9-2009
Revised date: 26-11-2009
Accepted date: 9-1-2010

Please cite this article as: Nicolosi D, Scalia M, Nicolosi VM, Pignatello R, Encapsulation in fusogenic liposomes broadens the spectrum of action of vancomycin against Gram-negative bacteria, *International Journal of Antimicrobial Agents* (2008), doi:10.1016/j.ijantimicag.2010.01.015

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Encapsulation in fusogenic liposomes broadens the spectrum of action of vancomycin against Gram-negative bacteria

Daria Nicolosi ^a, Marina Scalia ^b, Vito M. Nicolosi ^{a,*}, Rosario Pignatello ^c

^a *Department of Microbiological and Gynaecological Sciences, University of Catania, Catania, Italy*

^b *Department of Biomedical Sciences, Section of General and Cellular Biology and Molecular Genetics 'G. Sichel', University of Catania, Catania, Italy*

^c *Department of Pharmaceutical Sciences, University of Catania, Catania, Italy*

ARTICLE INFO

Article history:

Received 29 September 2009

Accepted 9 January 2010

Keywords:

Fusogenic liposomes

SUVET

Gram-negative bacteria

SEM

TEM

* Corresponding author. Present address: Dipartimento di Scienze

Microbiologiche e Ginecologiche, via Androne 81, I-95124 Catania, Italy. Tel.:

+39 095 250 4712; fax: +39 095 250 4753.

E-mail address: marvito@unict.it (V.M. Nicolosi).

ABSTRACT

Many antibacterial agents, including the glycopeptides, are inactive against Gram-negative bacteria because of their inability to cross the outer membrane of these cells. Different chemical and technological approaches have been described to circumvent such limitation. In this study, we aimed to apply the strategy of fusogenic liposomes, up to now used to carry biological compounds and materials inside cells, to localise a glycopeptide antibiotic, vancomycin (VAN), to the periplasmic space, thus allowing it to exert its bactericidal activity. Small unilamellar liposome vesicles were prepared by an extrusion procedure (SUVETs) from a phospholipid–cholesterol hemisuccinate mixture known for its fusogenic properties with the eukaryotic cell membrane. VAN was loaded with high efficiency into these vesicles and in microbiological experiments in vitro was shown to be able to inhibit to a different extent the growth of wild and standard Gram-negative bacterial strains. Minimum inhibitory concentrations as low as 6 mg/L were observed, for instance against clinical isolates of *Escherichia coli* and *Acinetobacter baumannii*. In comparison, neither the free antibiotic nor VAN-loaded ‘classical’ (non-fusogenic) liposomes showed any activity against the same bacteria. Scanning and transmission electron microscopy studies allowed confirmation that the produced SUVETs were able to adhere to and fuse with the external membrane of *E. coli*. According to preliminary experiments, this technological strategy can be proposed as a potentially successful way to enlarge the spectrum of activity of VAN.

1. Introduction

The distribution and activity of a drug in the body is largely a function of its physicochemical properties. An alternative approach to affect the intrinsic biodistribution of antibacterial drugs is provided by their encapsulation in colloidal carriers, which hide and protect the drug molecules from peripheral degradation, delivering it to an inaccessible target site, possibly also in a controlled and predictable manner [1–3].

In this perspective of targeting, liposomes have been the most studied systems. They possess the typical features of colloidal carriers, are biodegradable and biocompatible, and their composition and properties can be finely modulated to improve their interaction with and/or penetration through cell membranes [4,5]. Liposomes have shown a particular validity in the treatment of infections by intracellular bacteria [6–8].

Scarce cell interaction and uptake is at the basis of the limited potency of many antibiotics against infections. Microorganisms in infected tissues are further protected by various biological structures in their cell or around the infection. For instance, Gram-negative bacteria possess an outer membrane (OM), rich in lipopolysaccharide (LPS) and proteins, that covers and protects the internal peptidoglycan wall, by which it is separated by an aqueous periplasmic space [9]. Permeation through the OM is governed by porins, water-filled open channels that allow the movement of hydrophilic molecules across the

membrane. The properties of porins vary considerably among wild-type bacterial species, and their functional structure, size and expression (and hence the ability of an antibiotic to be taken up by a bacterial cell) may change in strains with acquired resistance [9,10].

Antibacterial drugs can cross the OM by two main pathways: hydrophobic compounds enter by a passive route, whereas hydrophilic antibiotics diffuse through porin channels. The lipid and protein compositions of the OM have a strong influence on the sensitivity of bacterial cells to antibiotics, and intrinsic drug resistance involving modifications of these macromolecules has been often reported [9,11–13].

For instance, alterations in the composition and size of porins and/or in the LPS of the OM have been shown to alter the sensitivity profiles of bacteria to some fluoroquinolones [14], β -lactam antibiotics [10], erythromycin and even some of the more recent macrolides [15].

Glycopeptides are tricyclic macromolecular peptides with a complex chemical structure and a high molecular weight (1450–1500 Da). Because of their high molecular weight and size, they are unable to pass through porins in the OM to reach the cell wall area, which represents their site of action; therefore, Gram-negative bacteria are intrinsically resistant to this class of antibiotics [16].

Among the glycopeptides, vancomycin (VAN) is largely used in the clinical treatment of severe infections caused by multiresistant Gram-positive bacteria such as staphylococci, enterococci, diphtheroid bacilli and clostridia. VAN inhibits the synthesis of peptidoglycan, the major component of the bacterial cell wall. Its mechanism of action is unusual since it binds with its peptide portion the terminal D-alanine-D-alanyl peptide portion of the peptidoglycan precursor. This mechanism of action does not readily permit mutation to resistance [17,18].

Encapsulation into or association of antibiotics with colloidal carriers can effectively improve their interaction with pathogenic microorganisms. Among these carriers, liposomes are vesicular systems mainly formed by amphipathic phospholipids structured in ordered bilayers, with aqueous spaces inside that allow hosting of hydrophilic molecules. Their nature and structure resemble the cell membrane, thus opening the potentiality for an efficacious interaction between these carriers and cells. Such interaction has been typically classified into four processes, namely adsorption, endocytosis, lipid exchange and fusion [19]. The latter phenomenon has been studied in detail by many authors because it offers the possibility for introducing drugs inside cells more easily [20–22].

A peculiar class of phospholipid vesicles has been called ‘fusogenic’ liposomes. In general, their bilayers show enhanced ability to interact in their liquid crystalline phase with cell membranes, favouring the reciprocal mixing and

release of vesicle content inside cells. Strategies to achieve fusogenic liposomes essentially consist of incorporating in the liposome composition either inactivated Sendai virus envelope components [23–26] or particular fusogenic lipids that make the liposomes more fluid and able to promote the destabilisation of biological membranes [27–30].

In the present work, we have investigated the latter approach by preparing fusogenic liposomes containing VAN, with the aim of extending its antibacterial activity to Gram-negative organisms. In particular, we sought to verify the hypothesis that fusogenic vesicles, up to now essentially studied to improve the penetration of liposomal drugs into mammalian cells, could be applied to the specific condition of Gram-negative bacterial cells, where the presence of the OM resembles the eukaryotic cell membrane.

Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) studies were also performed to visualise the interaction/fusion of these liposomes following incubation with Gram-negative bacterial cells.

2. Materials and methods

2.1. Chemicals

Dioleoylphosphatidylethanolamine (DOPE) and dipalmitoylphosphatidylcholine (DPPC) were purchased from Genzyme Pharmaceuticals (Liestal, Switzerland).

Vancomycin hydrochloride, cholesterol hemisuccinate (CHEMS) and cholesterol (CHOL) were purchased from Sigma-Aldrich Chimica Srl (Milan, Italy). Diethyl ether, phosphotungstic acid (PTA), glutaraldehyde and osmium tetroxide were purchased from Merck (Darmstadt, Germany). All other reactants and solvents were of analytical grade or higher (Sigma-Aldrich Chimica Srl).

2.2. Microbial strains

Ten wild strains of each of the following Gram-negative bacteria, isolated from clinical cases, were used: *Escherichia coli*; *Klebsiella* spp.; *Pseudomonas aeruginosa*; and *Acinetobacter baumannii*. The above clinical strains were identified by standard methods using control ATCC strains and correspond to the deposited type strains. *Escherichia coli* and *Klebsiella* spp. were identified by the API 20[®] kit, whilst *P. aeruginosa* and *A. baumannii* were identified using the API 20 NE[®] kit (bioMérieux Italia S.p.A., Bagnoli a Ripoli, Italy). Strains were enrolled in the experiment only when the result of the assay gave an 'excellent identification' score. Following identification, bacteria were stored at -80 °C in cryovials containing nutrient broth enriched with 20% glycerine.

As control bacteria, *P. aeruginosa* (ATCC 27853) and *E. coli* (ATCC 25922) were purchased from the American Type Culture Collection (Rockville, MD).

2.3. Liposome preparation and characterisation

Multilamellar liposome vesicles (MLVs) were first prepared by the reverse-phase evaporation technique [31]. Briefly, 15 mg of lipids (DOPE/DPPC/CHEMS in a 4:2:4 molar ratio) were dissolved in a round-bottomed glass tube with 2 mL of a 1:1 (v/v) chloroform–methanol mixture. The solution was evaporated to dryness under a dry nitrogen flow and the produced thin lipid film was further kept at ca. 35 °C under vacuum (T-50 oven; Büchi Labortechnik AG, Flawil, Switzerland) for 6 h to eliminate any solvent trace. To produce the liposomes, the lipid film was dissolved with 3 mL of diethyl ether; VAN (9 mg) was dissolved in 1 mL of a phosphate buffer solution (pH 7.4) and vortex-mixed for ca. 15 min with the ether solution to obtain an initial water-in-oil emulsion. To produce plain liposomes, 1 mL of the same buffer solution was added. The organic solvent was then removed off under vacuum (Rotavapor®; Büchi) to induce a phase inversion that gave an oil-in-water secondary emulsion. The water-bath temperature during the whole process was kept constant ca. 50 °C, i.e. a value higher than the phase transition temperature of DPPC. At the end, the liposome suspension was diluted to 3 mL with the same buffer solution. Conventional MLVs, used as control in the microbiological assay, were made with the same procedure starting from 10 mg of a DPPC/CHOL mixture (7:3, mol/mol).

To obtain the final desired monolamellar liposomes (SUVETs), the MLV suspension was manually extruded (LiposoFast™ Basic; Avestin Europe

GmbH, Mannheim, Germany) 19 times through polycarbonate membrane filters (pore diameter 100 nm).

SUVET mean size was determined by photon correlation spectroscopy (PCS) using a Zetamaster apparatus (Malvern Instruments Ltd., Malvern, UK).

Experiments were carried out using a 4.5 mW laser diode operating at 670 nm as light source. Size measurements were carried out at a fixed scattering angle of 90°. To obtain the mean diameter and polydispersity index of the colloidal suspensions, a third-order cumulant fitting correlation function was performed by a Malvern PCS submicron particle analyser. The real and imaginary refractive indexes were set at 1.59 and 0.0, respectively. The following parameters were used for experiments: medium refractive index, 1.330; medium viscosity, 1.0 mPa s, and dielectric constant, 80.4. Each sample (50 µL) was diluted with pro-injectione water to 10 mL to avoid multiscattering phenomena and placed in a quartz cuvette. Size analysis consisted of three series of ten measurements for each tested sample.

To determine the amount of VAN loaded in the liposomes, a 0.5 mL fraction of the SUVET was passed through a Sephadex G-50 column (Sigma) (eluent, phosphate buffer solution, pH 7.4) to remove the unencapsulated fraction of the antibiotic. The purified liposome suspension was treated with Triton X-100 (5% w/v), then filtered through 0.22 µm pore size 13 mm nylon membrane filters (Whatman International Ltd., Maidstone, UK) and submitted to high-pressure

liquid chromatography to calculate VAN concentration, according to a published analytical method [32]. Drug concentration was expressed either as the entrapment efficiency, corresponding to the percent drug remaining encapsulated in the liposomes with respect to the amount initially added, and as drug loading, i.e. μg of VAN per mL of vesicle suspension.

2.4. Microbiological assay

Minimum inhibitory concentrations (MICs) were determined by the standard broth microdilution method [33]. Each microplate well was filled with 100 μL of Müller–Hinton broth and then 100 μL of VAN-loaded SUVET suspension (corresponding to 300 μg drug/mL and 500 μg lipids/mL) or a corresponding volume of unloaded SUVETs as negative control was added. To test the free drug, 100 μL of an aqueous solution of VAN (300 $\mu\text{g}/\text{mL}$) was used. By following scalar dilutions with the same broth, the different drug concentrations were thus obtained. The control well consisted of 100 μL of Müller–Hinton broth. Five microlitres of each bacterial suspension was then added, suitably diluted with the same broth to achieve a final bacterial concentration of 10^5 colony-forming units/mL in each well. Microplates were then incubated at 37 °C for 24 h. Each experiment was performed three times; the measured antibacterial activity was expressed as the MIC range (see Table 1).

2.5. Transmission electron microscopy

For electron microscopy preparations, 100 μL of a suspension of DOPE/DPPC/CHEMS SUVETs was mixed with an overnight culture of a clinical isolate of *E. coli* (1×10^8 bacteria/mL) for 1 h at 37 °C under slow stirring. Bacteria in broth alone served as a control. A drop of the above suspension was layered on a Formvar-coated copper grid (Electron Microscopy Sciences, Fort Washington, PA) for 10 min at 37 °C. The grids were then negatively stained by dipping in 1% (w/v) PTA (pH 6.8) for 15 s. Observations were carried out using a Hitachi H-7000 transmission electron microscope (Hitachi High-Technologies Europe GmbH, Krefeld, Germany).

Some samples were processed for electron microscopy by a conventional method. Briefly, the bacteria–SUVET suspension was centrifuged and the pellet was re-suspended with 3% glutaraldehyde in 0.12 M phosphate buffer solution (pH 7.2) at 4 °C for 1 h. After fixation, the pellet was included in a cloth of fibrin, dehydrated through a graded series of acetone and embedded in Durcupan ACM (Fluka Chemika-Biochemika, Buchs, Switzerland). Ultrathin sections were double stained with uranyl acetate and lead citrate.

2.6. Scanning electron microscopy

A drop of bacteria–SUVET suspension was layered on a sterile cover glass and fixed with 3% glutaraldehyde in 0.12 M phosphate buffer solution (pH 7.2) at 4

°C for 1 h. The samples were post-fixed in 1% osmium tetroxide in the same buffer, dehydrated in ethanol, critical point dried and sputter coated with a 5 nm gold layer using an Emscope SM 300 (Emscope Laboratories, Ashford, UK). A Hitachi S-4000 (Hitachi High-Technologies America, Inc., Schaumburg, IL) field emission scanning electron microscope was used for the observations.

3. Results

To study the possibility of releasing VAN in the periplasmic space of Gram-negative bacterial cells, we selected a liposome composition already characterised in the literature for the preparation of fusogenic vesicles. A mixture of DPPC and DOPE, containing an amphiphilic derivative of cholesterol (i.e. CHEMS) [29], was used to prepare MLVs. Membrane extrusion of the latter produced the desired small unilamellar vesicles (SUVETs). The obtained SUVETs were submitted to a microbiological assay to compare the MIC values of free and encapsulated VAN against different Gram-negative bacterial strains. Experiments were performed in comparison with classical (non-fusogenic) DPPC/CHOL liposomes loaded with VAN as well as with empty (unloaded) DOPE/DPPC/CHEMS vesicles and the free antibiotic as controls.

SUVET liposomes were obtained by membrane extrusion of MLV suspensions. The latter were produced by a reverse-phase evaporation technique: in fact, the presence of VAN as the hydrochloride salt did not allow stable phospholipid

vesicles to be obtained using the classical thin-layer evaporation method (i.e. simple hydration of a lipid film with a buffered solution of the drug).

The MLV suspension was repetitively passed through a 100 nm polycarbonate membrane. The pores of the latter are almost cylindrical, and unilamellar or multilamellar vesicles larger than the pore diameter are reduced in size and lamellarity during passage through the pores, resulting in a final liposome size that corresponds to the mean size of the pores themselves [34]. As a consequence, uniform vesicles were obtained by this method with a mean size of 103.23 ± 2.87 nm and a polydispersity index of 0.037, which indicates a very high particle size homogeneity. A mean entrapment efficiency of 65.8% was registered, corresponding to a VAN concentration of 2.055 mg/mL of liposome suspension.

In the microbiological assay, free VAN was inactive against all of the tested Gram-negative strains (MIC > 512 mg/L). Conversely, when the drug was loaded in the fusogenic DOPE/DPPC/CHEMS SUVETs, remarkable MIC values were measured (Table 1), as low as 6 mg/L for clinical isolates of *E. coli* and *A. baumannii*.

As control experiments, both unloaded and VAN-loaded non-fusogenic DPPC/CHOL SUVETs as well as unloaded fusogenic DOPE/DPPC/CHEMS

SUVETs (tested at a lipid concentration equivalent to a drug concentration of 512 mg/L in VAN-loaded vesicles) were all unable to affect bacterial growth.

4. Discussion

The possibility of phospholipid vesicles fusing with the cell membrane has often been claimed at the basis of the success of liposomal formulations. For instance, encapsulation in liposomes allowed sub-MIC concentrations of tobramycin to act against Gram-negative and Gram-positive bacteria [35].

In this study, a 4:2:4 (mol/mol) DOPE/DPPC/CHEMS lipid mixture, already described in the literature to produce pH-sensitive liposomes [29], was chosen to prepare small unilamellar liposome vesicles able to interact and fuse with the cell membrane.

Kinetic studies showed that liposomes made of mixture of DOPE with other lipid components, such as oleic acid, distearoylphosphatidylglycerol or CHEMS, release their content into the cytoplasm after a short incubation time with cells [36–39]. In particular, the association of DOPE with CHEMS has in fact been recognised to impart vesicles a pH-dependent stability that allows selective fusion of liposomes with specific cell components to be achieved [38,40]. The exact mechanisms by which these liposomes traverse the cytoplasmic membrane barrier are not completely clear. However, it is likely that partial

fusion of vesicle bilayers with the cell membrane causes destabilisation of the latter, facilitating the release of liposome content into the cytoplasm.

The specific role of phosphatidylethanolamine or DOPE can be explained on the basis of the low hydration of these polar head-groups. The presence of DOPE in fact increases the lipophilicity of the liposomal membrane and reduces the energy of interaction among the lipid bilayers. The presence of DPPC was instead required to form stable liposomal bilayers, since the particular structure of DOPE led to an inverted hexagonal phase instead of a lamellar phase when the lipid was used alone [41].

In the present study, the fusogenic properties of DOPE/DPPC/CHEMS unilamellar vesicles have been exploited with the purpose of releasing the antibiotic not inside cells but specifically in the narrow area of periplasmic space of Gram-negative bacteria. As a consequence, the OM barrier can be bypassed and the antibiotic can operate its molecular activity at the level of the cell wall.

In the microbiological assay, free VAN displayed no activity against all of the tested bacterial strains. When the antibiotic was loaded in non-fusogenic DPPC/CHOL liposomes, no activity was observed against Gram-negative strains. Negative control tests confirmed that unloaded (empty) SUVETs, made both by DPPC/CHOL (non-fusogenic) or DOPE/DPPC/CHEMS (fusogenic), were also ineffective against the tested bacteria. In a separate experiment, the

extemporary addition of VAN to empty fusogenic liposomes, before addition of the suspension to culture wells, also did not produce any inhibitory activity.

However, the drug showed remarkable MIC values when loaded in fusogenic DOPE/DPPC/CHEMS SUVETs (Table 1). In particular, the activity shown against *A. baumannii* is particularly interesting since this microorganism is naturally sensitive to only a few antibiotics [42]. Even the least sensitive strain among those tested in this study, *P. aeruginosa*, showed an interesting MIC value (50 mg/L). The same order of activity was registered for the two reference ATCC bacterial strains used. Although it should be confirmed by specific assays, it is conceivable that the lower MIC values observed for *P. aeruginosa* and *Klebsiella* spp. were due to the production of mucus, which hinders contact with the liposomes.

The obtained in vitro results, however, supported the initial working hypothesis that the fusogenic properties of the chosen (phospho)lipid mixture were able to convey the active compound through the external membrane inside the periplasmic space, where its antibacterial activity can be exerted.

TEM analysis has often been used to confirm the interaction of liposomes with the bacterial cell membrane. For example, Omri and colleagues [43,44] have used TEM to show the ability of 'classical' DPPC or 1,2-distearoyl-*sn*-glycero-3-phosphocholine (DSPC)/CHOL liposomes to transfer aminoglycoside antibiotics

to resistant bacterial cultures, such as *P. aeruginosa* and *Burkholderia cenocepacia*. Similarly, Sachetelli et al. [45] used negatively charged vesicles with a low phase transition temperature to increase the release of tobramycin in the cytoplasm of resistant bacteria.

Thus, to obtain photographic evidence of the interaction of the prepared liposomes with the bacterial cells, SEM and TEM analysis were done on *E. coli* cultures incubated with DOPE/DPPC/CHEMS SUVETs. Figs 1–3 show the adherence of liposomes to bacteria and the ultrastructural modification following the fusion of some vesicles with the bacterial membrane, which led in some instances to a deformation of the cell membrane. In negative staining TEM analysis, liposomes (dark spheres) surrounding the bacterial cells are visible (Fig. 2A), and small or large liposomes fused with the OM of bacteria (Fig. 2B, arrows). Also using conventional visualisation (Fig. 3), the multilayered structure of the cell envelope was visible, with the arrow indicating the fusion of a large liposome with the OM of bacteria, which also appears deformed.

These results reinforce the supposition that the measured in vitro activity was due to a liposome-carried release of antibiotic inside the bacteria cells. Specific experiments with labelled liposomes have been planned to identify the localisation of the encapsulated probe inside bacterial cells after fusion with this kind of liposome. Furthermore, absence of any sign of bacterial cell injuries in

the microscopy analysis suggested that the tested liposome formulation was not cytotoxic.

The present liposomal formulation can be proposed for the local treatment of Gram-negative sustained infective conditions, such as burns where these bacteria have been largely found [46]. It is conceivable that the presence of eukaryotic cells and tissues will affect the selective fusion of these liposomes with the bacterial cells and this must require committed in vitro and in vivo studies. Moreover, in view of systemic use, the described formulation would need suitable tuning, for instance surface modification of liposomes with hydrophilic polymers, to attain a circulation time in the bloodstream long enough to reach the target sites.

However, the reported and somewhat expected results will prompt us to explore the feasibility of these fusogenic liposomes to improve the activity of other antibiotics against resistant microorganisms.

Acknowledgment

Prof. F. Castelli (University of Catania, Catania, Italy) is gratefully acknowledged for assistance in the liposome extrusion step.

Funding

This study was partially supported by the University of Catania (Progetti di Ricerca di Ateneo 2007).

Competing interests

None declared.

Ethical approval

Not required.

References

- [1] Coates AR, Hu Y. Novel approaches to developing new antibiotics for bacterial infections. *Br J Pharmacol* 2007;152:1147–54.
- [2] Fenske DB, Cullis PR. Liposomal nanomedicines. *Expert Opin Drug Deliv* 2008;5:25–44.
- [3] Yacoby I, Benhar I. Antibacterial nanomedicine. *Nanomed* 2008;3:329–41.
- [4] Alipour M, Halwani M, Omri A, Suntres ZE. Antimicrobial effectiveness of liposomal polymyxin B against resistant Gram-negative bacterial strains. *Int J Pharm* 2008;355:293–8.
- [5] Goyal P, Goyal K, Vijaya Kumar SG, Singh A, Katare OP, Mishra DN. Liposomal drug delivery systems—clinical applications. *Acta Pharm* 2005;55:1–25.
- [6] Briones E, Colino I, Lanao JM. Delivery systems to increase the selectivity of antibiotics in phagocytic cells. *J Control Release* 2008;125:210–27.
- [7] Carlone NA, Cuffini AM, Tullio V, Cavallo G. Interactions of antibiotics with phagocytes in vitro. *J Chemother* 1991;3(Suppl 1):98–104.
- [8] Gamazo C, Prior S, Concepción Lecároz M, Vitas AI, Campanaro MA, Pérez G, et al. Biodegradable gentamicin delivery systems for parenteral use for the treatment of intracellular bacterial infections. *Expert Opin Drug Deliv* 2007;4:677–88.
- [9] Pagès JM, James CE, Winterhalter M. The porin and the permeating antibiotic: a selective diffusion barrier in Gram-negative bacteria. *Nat Rev Microbiol* 2008;6:893–903.

- [10] James PA, Reeves DS. Bacterial resistance to cephalosporins as a function of outer membrane permeability and access to their target. *J Chemother* 1996;8(Suppl 2):37–47.
- [11] Hancock REW. Resistance mechanisms in *Pseudomonas aeruginosa* and other nonfermentative Gram-negative bacteria. *Clin Infect Dis* 1998;27(Suppl 1):S93–9.
- [12] Hancock REW, Brinkman FSL. Function of *Pseudomonas* porins in uptake and efflux. *Annu Rev Microbiol* 2002;56:17–38.
- [13] Vila J, Martí S, Sánchez-Céspedes J. Porins, efflux pumps and multidrug resistance in *Acinetobacter baumannii*. *J Antimicrob Chemother* 2007;59:1210–5.
- [14] Ruiz J. Mechanisms of resistance to quinolones: target alterations, decreased accumulation and DNA gyrase protection. *J Antimicrob Chemother* 2003;51:1109–17.
- [15] Vaara M. Outer membrane permeability barrier to azithromycin, clarithromycin, and roxithromycin in Gram-negative enteric bacteria. *Antimicrob Agents Chemother* 1993;37:354–6.
- [16] Quintiliani R Jr, Courvalin P. Mechanisms of resistance to antimicrobial agents. In: Murray PR, Baron EJ, Pfaller MA, Tenover FC, Tenover RH, editors. *Manual of clinical microbiology*. 6th ed. Washington, DC: ASM Press; 1995. p. 1319.

- [17] Chang S, Sievert DM, Hageman JC, Boulton ML, Tenover FC, Downes FP, et al. Infection with vancomycin-resistant *Staphylococcus aureus* containing the *vanA* resistance gene. N Engl J Med 2003;348:1342–7.
- [18] Reynolds PE, Courvalin P. Vancomycin resistance in enterococci due to synthesis of precursors terminating in D-alanyl-D-serine. Antimicrob Agents Chemother 2005;49:21–5.
- [19] Duzgunes N, Nir S. Mechanisms and kinetics of liposome–cell interactions. Adv Drug Deliv Rev 1999;40:3–18.
- [20] Goryacheva YA, Vekshina OM, Yashin VA, Kim YA. Fusion and endocytosis of anionic liposomes with Ehrlich ascitic carcinoma cells. Bull Exp Biol Med 2005;140:733–5.
- [21] Knoll G, Burger KN, Bron R, van Meer G, Verkleij AJ. Fusion of liposomes with the plasma membrane of epithelial cells: fate of incorporated lipids as followed by freeze fracture and autoradiography of plastic sections. J Cell Biol 1988;107:2511–21.
- [22] Watabe A, Yamaguchi T, Kawanishi T, Uchida E, Eguchi A, Mizuguchi H, et al. Target-cell specificity of fusogenic liposomes: membrane fusion-mediated macromolecule delivery into human blood mononuclear cells. Biochim Biophys Acta 1999;1416:339–48.
- [23] Dzau VJ, Mann MJ, Morishita R, Kaneda Y. Fusogenic viral liposome for gene therapy in cardiovascular diseases. Proc Natl Acad Sci USA 1996;93:11421–5.

- [24] Goto T, Morishita M, Nishimura K, Nakanishi M, Kato A, Ehara J, et al. Novel mucosal insulin delivery systems based on fusogenic liposomes. *Pharm Res* 2006;23:384–91.
- [25] Kunisawa J, Nakagawa S, Mayumi T. Pharmacotherapy by intracellular delivery of drugs using fusogenic liposomes: application to vaccine development. *Adv Drug Deliv Rev* 2001;52:177–86.
- [26] Nakanishi M, Mizuguchi H, Ashihara K, Senda T, Eguchi A, Watabe A, et al. Gene delivery systems using the Sendai virus. *Mol Membr Biol* 1999;16:123–7.
- [27] Boomer JA, Qualls MM, Inerowicz HD, Haynes RH, Patri VS, Kim JM, et al. Cytoplasmic delivery of liposomal contents mediated by an acid-labile cholesterol–vinyl ether–PEG conjugate. *Bioconjug Chem* 2009;20:47–59.
- [28] Karanth H, Murthy RS. pH-sensitive liposomes—principle and application in cancer therapy. *J Pharm Pharmacol* 2007;59:469–83.
- [29] Sakaguchi N, Kojima C, Harada A, Koiwai K, Kono K. The correlation between fusion capability and transfection activity in hybrid complexes of lipoplexes and pH-sensitive liposomes. *Biomaterials* 2008;29:4029–36.
- [30] Templeton NS. Nonviral delivery for genomic therapy of cancer. *World J Surg* 2009;33:685–97.
- [31] Lasch J, Weissig V, Brandl M. Preparation of liposomes. In: Torchilin VP, Weissig V, editors. *Liposomes—a practical approach*. 2nd ed. Oxford, UK: Oxford University Press; 2003. p 3–30.

- [32] Jehl F, Gallion C, Thierry RC, Monteil H. Determination of vancomycin in human serum by high-pressure liquid chromatography. *Antimicrob Agents Chemother* 1985;27:503–7.
- [33] Clinical and Laboratory Standards Institute. *Performance standards for antimicrobial susceptibility testing*. Seventeenth informational supplement. Document M100-S17. Wayne, PA: CLSI; 2007.
- [34] Hope MJ, Nayar R, Mayer LD, Cullis PR. Reduction of liposome size and preparation of unilamellar vesicles by extrusion techniques. In: Gregoriadis G, editor. *Liposome technology*, Vol. 1. 2nd ed. Boca Raton, FL: CRC Press; 1993. p 123–39.
- [35] Beaulac C, Sachetelli S, Lagace J. In-vitro bactericidal efficacy of sub-MIC concentrations of liposome-encapsulated antibiotic against Gram-negative and Gram-positive bacteria. *J Antimicrob Chemother* 1998;41:35–41.
- [36] Guo X, Szoka FC Jr. Steric stabilization of fusogenic liposomes by a low-pH sensitive PEG–diortho ester–lipid conjugate. *Bioconjug Chem* 2001;12:291–300.
- [37] Lubrich B, van Calker D, Peschka-Süss R. Inhibition of inositol uptake in astrocytes by antisense oligonucleotides delivered by pH-sensitive liposomes. *Eur J Biochem* 2001;267:2432–8.
- [38] Kono K, Iwamoto M, Nishikawa R, Yanagie H, Takagishi T. Design of fusogenic liposomes using a poly(ethylene glycol) derivative having amino groups. *J Control Release* 2000;68:225–35.

- [39] Mok KW, Cullis PR. Structural and fusogenic properties of cationic liposomes in the presence of plasmid DNA. *Biophys J* 1997;73:2534–45.
- [40] Simões S, Slepishkin V, Düzgünes N, Pedroso de Lima MC. On the mechanisms of internalization and intracellular delivery mediated by pH-sensitive liposomes. *Biochim Biophys Acta* 2001;1515:23–37.
- [41] Epand RM, Fuller NL, Rand RP. Role of the position of unsaturation on the phase behavior and intrinsic curvature of phosphatidylethanolamines. *Biophys J* 1996;71:1806–10.
- [42] Abbo A, Carmeli Y, Navon-Venezia S, Siegman-Igra Y, Schwaber MJ. Impact of multi-drug-resistant *Acinetobacter baumannii* on clinical outcomes. *Eur J Clin Microbiol Infect Dis* 2007;26:793–800.
- [43] Halwani M, Mugabe C, Azghani AO, Lafrenie RM, Kumar A, Omri A. Bactericidal efficacy of liposomal aminoglycosides against *Burkholderia cenocepacia*. *J Antimicrob Chemother* 2007;60:760–9.
- [44] Mugabe C, Halwani M, Azghani AO, Lafrenie RM, Omri A. Mechanism of enhanced activity of liposome-entrapped aminoglycosides against resistant strains of *Pseudomonas aeruginosa*. *Antimicrob Agents Chemother* 2006;50:2016–22.
- [45] Sachetelli S, Khalil H, Chen T, Beaulac C, Sénéchal S, Lagacé J. Demonstration of a fusion mechanism between a fluid bactericidal liposomal formulation and bacterial cells. *Biochim Biophys Acta* 2000;1463:254–66.

- [46] Albrecht MC, Griffith ME, Murray CK, Chung KK, Horvath EE, Ward JA, et al. Impact of *Acinetobacter* infection on the mortality of burn patients. J Am Coll Surg 2006;203:546–50.

Fig. 1. Scanning electron microscopy images of an overnight culture of (A) *Escherichia coli* and (B) the same strain incubated with fusogenic SUVETs for 1 h at 37 °C. Bar, 2 µm. SUVETs, small unilamellar liposome vesicles prepared by an extrusion procedure.

Fig. 2. Transmission electron microscopy image of (A) liposome–bacteria interaction and (B) fusion (arrows) of an overnight *Escherichia coli* culture incubated with fusogenic SUVETs for 1 h at 37 °C as observed by negative staining. Bars, 100 nm (A) and 200 nm (B). SUVETs, small unilamellar liposome vesicles prepared by an extrusion procedure.

Fig. 3. Transmission electron microscopy micrograph of an ultrathin section of *Escherichia coli* cell in the presence of fusogenic SUVETs, as observed by the conventional method. Bar, 100 nm. SUVETs, small unilamellar liposome vesicles prepared by an extrusion procedure.

Table 1

Minimum inhibitory concentration ranges (mg/L) of VAN-loaded
DOPE/DPPC/CHEMS SUVETs and free VAN against different Gram-negative
bacterial strains ^a

	<i>Escherichia coli</i>	<i>Klebsiella</i> spp.	<i>Pseudomonas aeruginosa</i>	<i>Acinetobacter baumannii</i>	<i>E. coli</i> ATCC 25922	<i>P. aeruginosa</i> ATCC 27853
SUVETs	6–25	25–50	50	6–12.5	10.5	83.7
VAN	>512	>512	>512	>512	>512	>512

VAN, vancomycin; DOPE, dioleoylphosphatidylethanolamine; DPPC, dipalmitoylphosphatidylcholine; CHEMS, cholesterol hemisuccinate; SUVETs, small unilamellar liposome vesicles prepared by an extrusion procedure.

^a Ten wild strains for each species were tested.





