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PII: S0005-2736(17)30187-6
DOI: doi:[10.1016/j.bbamem.2017.06.006](https://doi.org/10.1016/j.bbamem.2017.06.006)
Reference: BBAMEM 82519

To appear in: *BBA - Biomembranes*

Received date: 1 March 2017
Revised date: 10 May 2017
Accepted date: 8 June 2017



Please cite this article as: Marianna Mamusa, Leopoldo Sitia, Francesco Barbero, Angels Ruyra, Teresa Díaz Calvo, Costanza Montis, Ana Gonzalez-Paredes, Grant N. Wheeler, Christopher J. Morris, Michael McArthur, Debora Berti, Cationic liposomal vectors incorporating a bolaamphiphile for oligonucleotide antimicrobials, *BBA - Biomembranes* (2017), doi:[10.1016/j.bbamem.2017.06.006](https://doi.org/10.1016/j.bbamem.2017.06.006)

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Cationic liposomal vectors incorporating a bolaamphiphile for oligonucleotide antimicrobials

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ABSTRACT

Antibacterial resistance has become a serious crisis for world health over the last few decades, so that new therapeutic approaches are strongly needed to face the threat of resistant infections. Transcription factor decoys (TFD) are a promising new class of antimicrobial oligonucleotides with proven *in vivo* activity when combined with a bolaamphiphilic cationic molecule, 12-bis-THA. These two molecular species form stable nanoplexes which, however, present very scarce colloidal stability in physiological media, which poses the challenge of drug formulation and delivery. In this work, we reformulated the 12-bis-THA/TFD nanoplexes in a liposomal carrier, which retains the ability to protect the oligonucleotide therapeutic from degradation and deliver it across the bacterial cell wall. We performed a physical-chemical study to investigate how the incorporation of 12-bis-THA and TFD affects the structure of POPC- and POPC/DOPE liposomes. Analysis was performed using dynamic light scattering (DLS), ζ -potential measurements, small-angle x-ray scattering (SAXS), and steady-state fluorescence spectroscopy to better understand the structure of the liposomal formulations containing the 12-bis-THA/TFD complexes. Oligonucleotide delivery to model *Escherichia coli* bacteria was assessed by means of confocal scanning laser microscopy (CLSM), evidencing the requirement of a fusogenic helper lipid for transfection. Preliminary biological assessments suggested the necessity of further development by modulation of 12-bis-THA concentration in order to optimize its therapeutic index, *i.e.* the ratio of antibacterial activity to the observed cytotoxicity. In summary, POPC/DOPE/12-bis-THA liposomes appear as promising formulations for TFD delivery.

KEYWORDS

Antimicrobial resistance; Cationic liposomes; Oligonucleotide therapeutics; Transfection; Small-angle x-ray scattering

1. Introduction

The emergence of drug-resistant microbial strains is a natural phenomenon that occurs when bacteria evolve and adapt to face the threats posed by antimicrobial agents [1]. However, this process has been greatly accelerated by the excessive and incorrect use of antibacterial drugs. This has resulted in the lack of available treatments for once curable infectious diseases [2,3], determining a world-wide health crisis as reported by the World Health Organization [4]. In this context, renewed interest by public and private initiatives has focused on innovative approaches [5]. Among several alternative approaches proposed [6–11], transcription factor decoys (TFD) have shown the potential to defeat resistant infections, such as those caused by *Clostridium difficile* in animal models [12], when combined with a bolaamphiphilic cationic delivery molecule (12-bis-THA) to form nanosized association complexes, termed nanoplexes.

TFDs are short oligonucleotides consisting of base sequences that mimic the binding site to transcription factors, and they can block essential genetic pathways in bacteria, thereby preventing their survival response against antimicrobial attack [13]. The cationic surfactant 12-bis-THA is a bolaamphiphile with a molecular structure reminiscent of dequalinium, which is prescribed as a topical treatment for various bacterial infections. Besides its intrinsic antibacterial activity, owing to the positive electrostatic charge, dequalinium has been studied as a scaffold for gene delivery systems [14]. Similarly, 12-bis-THA plays a fundamental role in forming nanoplexes with oligonucleotides, which are condensed into a *psi*-form [15]: this structural rearrangement affords both resistance to DNA degradation [16] and DNA delivery into live cells [17]. The condensation process is reversible, as the fully renatured oligonucleotide can be released from the complex with 12-bis-THA by displacing it with a competing anionic molecule [15].

12-bis-THA/TFD nanoplexes have been shown to be active in animal studies [17], but it is known that their colloidal stability needs to be improved prior to preclinical development, as they have the tendency to form insoluble precipitates in conditions of physiological ionic strength. The

optimized delivery system would also have controllable physical-chemical properties, as these affect the biodistribution of the nanoplexes and thus which infections can be treated. All of these requirements can be met by liposomes (or small unilamellar vesicles, SUV): these can be formulated from biocompatible lipids, and they have been successfully used as drug carriers [18] and transfection vectors [19]. In particular, several antibiotics already commercially distributed are formulated on a liposomal scaffold [20], and liposomes have been proposed as antisense DNA vectors to bacteria [21].

In the present work, we redesigned the 12-bis-THA/TFD antimicrobial complex in a stable liposomal formulation that can retain delivery to the bacterial cytoplasm. Given the amphiphilic nature of 12-bis-THA, the encapsulation of nanoplexes in liposomes poses some challenges. A physical-chemical study was therefore necessary to assess the possible influence of the payload on liposomal stability and bilayer integrity [22,23]. Therefore, we first investigated the effect of 12-bis-THA on the structure of liposomes based on classic lipids, *i.e.* neat POPC or a POPC/DOPE mixture; next, the formulations were investigated in depth to elucidate the nanoscale features of the bilayer, focusing in particular on the POPC/DOPE scaffolds. A preliminary biological evaluation was carried out to assess the transfection ability to model bacteria, the antibacterial activity and the cytotoxicity of these promising formulations.

2. Materials and methods

Materials

POPC (1-palmitoyl-2-oleoyl-sn-glycero-3-phosphocholine) and DOPE (1,2-dioleoyl-sn-glycero-3-phosphoethanolamine) were purchased from Avanti PolarLipids (Alabaster, AL).

12-bis-THA (1,1'-(dodecane-1,12-diyl)-bis-(9-amino-1,2,3,4-tetrahydroacridinium) (chloride or iodide) was synthesized by Shanghai Chempartners & co. LTD.

Ultrapure water was obtained by means of a Millipore Elix® 3 water purification system.

Oligonucleotide synthesis

The oligonucleotide TFDs used in this work were manufactured and purified through HPLC at AxoLabs (Kulmbach, Germany). The TFD used for structural studies has been described elsewhere [15]; it consists of 77 base pairs containing the binding site for the sigma factors of RNA polymerase SigH. The fluorescently labeled Alexa488-Fur TFD was used in imaging and biological assays and contained the binding site for *E. coli* Fur transcription factor. Its sequence was: 5'-Alexa488-TEG-CGA TAG AAG TGG ATT TTT CCA CTT CTA* T*C*G-3', where TEG is a tetraethyl glycol linker and the last nucleotides followed by an asterisk contain a phosphorothioate backbone.

Stability of 12-bis-THA/TFD nanoplexes

To prepare 12-bis-THA/TFD nanoplexes in water, 500 μ L of a water stock solution of 12-bis-THA at a concentration of 0.23 mg/mL were mixed with 490 μ L H₂O and vortexed for 30 s. Then, 10 μ L of TFD aqueous solution (1 mg/mL) were added, and vortexed for 30 s more. The nanoplexes thereby obtained were characterized by a positive-to-negative charge ratio $Z_{+/-} = 11$.

To prepare particles in saline solutions, 500 μ L of a water stock solution of 12-bis-THA at a concentration of 0.23 mg/mL were mixed with 390 μ L H₂O and vortexed for 30 s. Then, 10 μ L of

TFD aqueous solution (1 mg/mL) were added, and vortexed for 30 s more. Finally, 100 μ L of 1.5 mol/L solutions of sodium chloride (NaCl) and sodium citrate (Na₃Cit) were added to the particle solution.

Preparation of multilamellar vesicles and liposomes

The lipids POPC and DOPE were weighed in order to obtain a POPC:DOPE = 7:3 weight ratio, in such a way as to obtain a final total concentration of 5 mg/mL lipids in the liposomal suspensions. The lipids were firstly dissolved and thoroughly mixed in chloroform or chloroform/methanol. The solvent was evaporated using a gentle N₂ flow, and the lipid films were further dried by vacuum pumping for at least 8 hours. The films were hydrated with water or with a TFD solution, depending on the particular protocol, and the mixture was vortexed to obtain a suspension of multilamellar vesicles. In a typical sample, the lipids-to-12-bis-THA mole ratio would be 20:1, while the mole ratio between the bolaamphiphile and the oligonucleotide would be 860:1 (which affords $Z_{+/-} = 11$), unless specified differently.

In order to obtain liposomes, the mixture underwent ten freeze-and-thaw cycles (from liquid nitrogen to a 50 °C water bath), unless the oligonucleotide was already present. Eventually, the suspension was extruded ten times through a polycarbonate filter (pore size = 100 nm). If 12-bis-THA was not in the initial dry film, it would be incorporated in the liposomes by a surface decoration method as follows: the bolaamphiphile was dissolved in methanol, then a dry film was obtained by evaporating the solvent under N₂, and the appropriate amount of liposomal dispersion was poured on top of the dry film. The sample was vortexed and then kept in orbital stirring for approximately 10 hours.

12-bis-THA quantification in liposomes

The concentration of 12-bis-THA in the liposomes was ascertained by HPLC analysis, using a Zorbax Eclipse XDB-C18 column (150 \times 4.6 mm, 5 μ m). The chromatography was carried out at

a flow rate 1 mL/min in isocratic conditions, where the mobile phase was KH_2PO_4 (20 mM)/acetonitrile/triethylamine (60:40:0.5 v/v/v) at pH = 3.8. UV-detection of 12-bis-THA was performed at $\lambda = 254$ nm.

TFD quantification in liposomes

The TFD concentration in liposomes was assessed using the Quant-iT™ OliGreen® fluorescent DNA staining dye (Life Technologies). A fluorescence intensity vs. TFD concentration standard curve was realized by recording the emission spectra of OliGreen® on a LS50B spectrofluorimeter (Perkin-Elmer, Italy); the spectra were acquired in the corrected mode, with an excitation wavelength of 480 nm and 10 nm slits, and the intensity at the emission maximum (520 nm) was plotted against [TFD]. Liposomal samples were diluted appropriately to fit in the linear range. The amount of TFD encapsulated in the liposomes was estimated by measuring the fluorescence of the OliGreen dye before and after the disruption of liposomes with 1 wt% Triton X-100. For each sample, 3 acquisitions were collected at 25 °C and averaged.

Differential scanning calorimetry (DSC)

DSC analysis was performed with a Q2000 DSC, TA Instruments (New Castle, USA). Roughly 30 mg of each sample were placed in aluminum hermetic pans and analyzed scanning the temperature between 0 °C and 50 °C at 5 °C/min.

Dynamic light scattering (DLS)

DLS analysis was used to infer the size and polydispersity of 12-bis-THA/TFD nanoplexes and of liposomes. For the nanoplexes, a Malvern ZetaSizer ZS was used, having a red laser ($\lambda = 630$ nm) and the detector placed at 173°. For the liposomes, the instrument used was a Brookhaven BI9000-AT digital autocorrelator, equipped with a green laser ($\lambda = 532$ nm; Torus, mpc3000, LaserQuantum, UK) and an APD detector placed at 90°. In both cases, the hydrodynamic

diameters were calculated by cumulant analysis of the autocorrelation functions to extract the diffusion coefficients of the dispersed particles, which were then converted into sizes by assuming a spherical shape via the Stokes-Einstein equation.

Zeta-potential measurements

ζ -potentials were obtained from phase analysis light scattering (PALS) analysis, performed on a Brookhaven ZetaPALS instrument, equipped with a laser operating at 659 nm. The scattered intensity was collected at 15° to determine the electrophoretic mobility; the ζ -potentials were then calculated through the Helmholtz–Smoluchowski equation.

Small angle x-ray scattering (SAXS)

SAXS analysis of multilamellar vesicles was carried out with a Kratky camera system (HECUS). The incident beam was a CuK_α radiation ($\lambda = 1.542 \text{ \AA}$) produced by a sealed-tube generator (Seifert ID-303) operating at 1.5 kW; the CuK_β radiation was removed thanks to a 10 μm thick Ni filter. The detector (OED 50 M) contained 1024 channels of width 54 μm , and the sample-to-detector distance was 274 mm. The available Q-range was 0.01-0.55 \AA^{-1} . All measurements were performed at 25 °C (temperature controlled by a Peltier element, accuracy $\pm 0.1 \text{ }^\circ\text{C}$); the samples were inserted in either a quartz Mark capillary (1.5 mm diameter) or a paste sample holder, depending on their viscosity, and the cells were kept under vacuum during the experiment.

SAXS analysis of liposomes was conducted at the Austrian SAXS beamline (Elettra Synchrotron, Trieste, Italy). The samples were placed in quartz Mark capillaries of 1 mm thickness, enclosed in a steel cell; the same capillary was used for the blank to subtract to each sample. Scattering patterns were recorded at room temperature, on a Mar300-image-plate detector (MarResearch, Norderstedt, Germany), by irradiating the samples with an x-ray beam at an 8 keV energy. Irradiation times were in the order of 30 seconds, and for each sample 3 spectra were

acquired and averaged. The sample-to-detector distance of 1308 mm allowed to access a 0.0067-0.46 Å⁻¹ Q-range.

Data reduction and background subtraction were performed with the software IGOR Pro (Wavemetrics, Inc.) [24]. Curves obtained with the Kratky camera were iteratively desmeared using the procedure reported by Lake [25]. Data modelling was carried out with the software GAP, provided by Prof. Georg Pabst (Graz University, Austria) [26].

Confocal laser scanning microscopy (CLSM)

E. coli strain DH5 α was grown to mid-log growth (Optical Density 0.2 - 0.3 at 630 nm) in LB broth. Fresh culture was mixed with an equal volume of liposomes loaded with an Alexa-Fluor488-labelled TFD (λ ex488/em519) and incubated at room temperature for a total of 1.5 hours, under constant agitation in the dark. For the last 30 minutes, the bacterial membrane was labelled with the fluorescent membrane dye WGA-TMR (λ ex555/em580 nm, Life Technologies, UK) at a final concentration of 10 μ g/ml. The samples were smeared onto poly-L-lysine coated slides (Sigma-Aldrich, UK) and incubated for a further 1 hour in the dark at room temperature. Slides were then gently washed with filtered-sterilized PBS and dried in the air. Microscopy slides were kept in the dark at 4 °C prior to analysis by confocal microscopy using either a Leica TCS SP5 confocal microscope or a Leica TCS SP2, using a 63 \times oil immersion objective or a 63 \times water immersion objective, respectively. In both cases, the images were acquired with 488 nm Argon laser excitation (λ em498/ex530 nm) for Alexa488-labeled TFD and with DPSS 561 nm laser excitation (λ em571/ex620 nm) for WGA-TMR dye labeling the bacterial membrane.

Biological assays

Brief experimental methods for three biological assays are included below. Further details can be found in the Supplementary Methods section.

-Antibacterial activity (MIC test). The antibacterial activity of 12-bis-THA-containing formulations was tested against *Escherichia coli* DH5 α using standard procedures, where changes in the optical density (630 nm) after overnight growth is interpreted as bacterial growth inhibition. Bacteria were incubated with liposomes in a concentration range between 5.3×10^{-4} and 5.3×10^{-7} mol/L for the lipids (corresponding to 18 - 0.018 μ mol/L for 12-bis-THA and 1 - 0.001 μ g/mL for TFDs).

-In vitro cytotoxicity studies (MTT assay). Caco-2 cells were grown to 70-80% confluency in 96 well plates, then exposed to liposomes in a concentration range of lipids between 2.65×10^{-3} and 1×10^{-5} mol/L (corresponding to 90 μ mol/L and 0.34 μ mol /L of 12-bis-THA and 5 to 0.02 μ g/mL of TFDs) in serum-free culture medium. After 24 h the formulation was removed and the cell viability examined by measuring the mitochondrial reduction of MTT using $A_{570\text{nm}}$.

-Xenopus laevis toxicity assay. All experiments were performed in compliance with the relevant laws and institutional guidelines at the University of East Anglia. The research has been approved by the local ethical review committee according to UK Home Office regulations. *Xenopus laevis* embryos were obtained as previously described [27]. *X. laevis* embryos at stage 38 were exposed to liposomes \pm 12-bis-THA and TFD at concentrations ranging from 2.65×10^{-3} to 4×10^{-5} mol/L of lipids, corresponding to 90 μ mol/L and 1.36 μ mol /L of 12-bis-THA and 5 to 0.08 μ g/mL of TFDs. Embryos were incubated at 18 $^{\circ}$ C until they reached stage 45.

3. Results and Discussion

We recently showed, using a range of complementary physical techniques, that 12-bis-THA (Scheme 1) complexes TFDs into a highly compacted, nuclease-resistant “*psf*” form in aqueous solution [15].

Scheme 1. Molecular structure of 12-bis-THA.

Here we studied the kinetics of nanoplex stability by dynamic light scattering (DLS), monitoring the variation of hydrodynamic diameter (D_H) and average scattered intensity (I_{av}) in water and in saline media at physiological ionic strength. As illustrated in Figure 1A, nanoplexes in H₂O stored at 4 °C were stable for at least 72 h in terms of size. The stability of particles in water at RT (Figure 1B) was limited to 24 h, when they were observed to become slightly larger; in seven days, the size had increased by almost 100% while the scattering intensity was reduced by 7.5 times (data not shown). Indeed, since the light scattered by colloidal objects in solution is proportional to their concentration, such a dramatic decline of I_{av} clearly indicates the steep decrease of the number of suspended particles in solution as they progressively precipitate. The few particles remaining in suspension became larger over time due to coalescence and would most likely precipitate in time. Near instantaneous aggregation was observed after incubating the nanoplexes in saline solutions with physiological ionic strength (sodium citrate or sodium chloride, 150 mM). This phenomenon is expected, due to the electrostatic origin of colloidal stability in water. The screening of the electrostatic charge of ionic colloids in the presence of dissolved salts, according to the DLVO theory of colloidal stability, triggers aggregation and eventually precipitation [28]. At the same time, this denotes the marked instability of the 12-bis-THA/TFD

antibacterial complex in saline media. In light of these results, we resorted to the reformulation of the 12-bis-THA/TFD nanoplexes in a lipid-based scaffold.

Figure 1. Colloidal stability of 12-bis-THA/TFD polyplexes in different media: (A) water, 4 °C; (B) water, RT; (C) NaCl 150 mM, RT; (D) sodium citrate 150 mM, RT. Samples were analysed by light scattering analysis. D_H (nm) = hydrodynamic diameter; I_{av} (kcps) = average scattering intensity. Lines are not data fits but a guide for the eye. Data shown are mean \pm standard deviation.

Reformulation of nanoplexes into POPC- and POPC/DOPE liposomes

Liposomes for drug delivery are typically obtained with biocompatible lipids. We report here on the incorporation of 12-bis-THA and the loading of a model TFD in two lipid systems: one based on pure POPC and another based on the mixture of POPC and DOPE (1,2-dioleoyl-sn-glycero-3-phosphoethanolamine) in a 7:3 weight ratio. DOPE has been used for a long time as a helper lipid to promote fusion of liposomes with biological membranes, with proven ability to boost DNA transfection [29] and antibiotic efficacy [30].

The symmetric bolaamphiphile 12-bis-THA is poorly soluble in water and does not behave like a typical surfactant, as it has no clear-cut critical micellar concentration [15]. However, the presence of two cationic headgroups along with a 12-C aliphatic chain spacer suggests the possibility of amphiphilic behaviour. In order to assess the effect of the bolaamphiphile on the integrity of lipid bilayers, we firstly incorporated 12-bis-THA into liposomes following two different paths. In the “co-extrusion method”, 12-bis-THA (0.2 mM) was mixed with other lipids (5 mg/mL) in the initial dry film before hydration and membrane extrusion. In the “surface

decoration method”, pre-extruded liposomes were added to a dry film of 12-bis-THA to allow the uptake of the bolaamphiphile into the bilayers. The two protocols are represented in Scheme 2.

Scheme 2. Pictorial representation of the two protocols employed for liposome preparation.

- a) “Co-extrusion” method: lipids and 12-bis-THA are both present in the initial dry film;
 b) “Surface decoration” method: only lipids are present in the initial dry film; 12-bis-THA is added to liposomes after extrusion.

Composition		D_H (nm)	PDI	ζ -Pot (mV)
POPC		109 ± 1	0.07	-23 ± 2
POPC + 12-bis-THA (20:1 mole ratio)	co-extruded	105 ± 2	0.09	$+20 \pm 3$
	decoration	120 ± 2	0.10	$+16 \pm 1$
POPC/DOPE		111 ± 2	0.04	-16 ± 4
(POPC/DOPE) + 12-bis-THA (20:1 mole ratio)	co-extruded	115 ± 4	0.04	$+20 \pm 1$
	decoration	124 ± 2	0.16	$+28 \pm 2$

Table 1. Physical-chemical characterization of liposomes (lipids: 5 mg/mL, with POPC:DOPE = 70:30 %wt) without and with 12-bis-THA, incorporated *via* two different protocols. Hydrodynamic diameters (D_H , nm) and size polydispersity (PDI) obtained by cumulant analysis of the DLS autocorrelation functions; ζ -potentials (ζ -Pot, mV) obtained by PALS analysis of the same samples. Data are mean \pm standard deviation.

The physical-chemical characterization of such liposomes is given in Table 1. For both POPC- and POPC/DOPE systems, the initial negative ζ -potentials of pure liposomes reversed upon introduction of 12-bis-THA, confirming the binding of the bolaamphiphile to liposomes with both methods. The co-extrusion protocol originated smaller POPC- and POPC/DOPE liposomes than

the decoration method, suggesting that in the former 12-bis-THA partitions between the inner and outer leaflet of the bilayer, while in the latter the bolaamphiphile accumulates at the liposomal surface. Importantly, the ζ -potentials of the vesicles decorated with 12-bis-THA remained constant around the value +25 mV (within the error bar; data not shown) even after an 80-fold dilution, demonstrating that the bolamphiphile is strongly associated with the bilayer and does not desorb upon dilution.

Although the hydrodynamic size increased, 12-bis-THA did not change the morphology of liposomes, as demonstrated in a cryo-TEM image (Figure S1, Supporting Information) showing spherical liposomes made of POPC and 12-bis-THA introduced by surface decoration. Most importantly, POPC- and POPC/DOPE liposomes containing 12-bis-THA did not show any precipitation or other signs of colloidal instability when diluted 1:10 and 1:20 with high ionic strength media such as LB broth NaCl 150 mM solution (data not shown), contrary to the neat 12-bis-THA/TFD nanoplexes.

However, HPLC analysis of the liposomal dispersions obtained by co-extrusion revealed that approximately 50% of the 12-bis-THA was incorporated into the final liposome suspension (data not shown). Similarly, we encountered a loss of oligonucleotide when loading a model TFD (12-bis-THA/TFD charge ratio $Z_{+/-} = 22$) into the liposomes using the co-extrusion protocol. Indeed, the extrusion process was extremely slow and difficult, suggesting rapid adsorption of material on the polycarbonate membrane. The TFD content in the extruded formulation was assessed by staining with the DNA-binding fluorescent probe OliGreen[®], and compared to the TFD content of the dispersion of multilamellar vesicles (MLV) before extrusion (see Figure S2, Supporting Information). The assay yielded 84% ($\pm 10\%$) of the theoretical TFD amount in the MLV dispersion after disruption of the membranes with Triton X-100, while in the extruded liposomes no DNA could be detected. This suggests that all the TFD was lost during the extrusion process.

Several hypotheses can be formulated to possibly explain the loss of material described above. Firstly, DSC experiments ruled out the possible increase in the gel-to-fluid transition temperature,

T_m , for the lipid bilayers. Indeed, no transition peaks were observed in the 4 °C – 80 °C range (data not shown), which suggests that these lipid assemblies should be easily extruded at room temperature. In another possible scenario, the presence of both the TFD and 12-bis-THA in the initial lipid dry film may promote the formation of the strong complex between the two species directly in the hydrated bilayers, producing lipoplexes in a columnar phase, as observed in similar systems [31]. These species are often rigid and larger than 100 nm, with a greater propensity to obstruct the membrane pores, impeding the passage of the dispersion. In order to examine for such liquid-crystalline phases, we carried out a small-angle x-ray (SAXS) investigation of the POPC/DOPE MLV systems, without and with added bolaamphiphile or TFD, before extrusion.

Figure 2. SAXS patterns of POPC/DOPE bilayers: (A) neat; (B) with TFD; (C) with 12-bis-THA (20:1 mole ratio); (D) with 12-bis-THA and TFD ($Z_{+/-} = 22$).

As shown in Figure 2, MLVs of POPC/DOPE without and with TFD (Figure 2A,B) display the typical pattern of a lamellar phase with Bragg peaks, which occur at $Q = 2\pi/d$ values due to the interaction between adjacent lipid bilayers. From the first Bragg reflection order, we obtained the lamellar repeat spacing $d = 62.8 \text{ \AA}$ for both samples (without and with TFD), indicating that there is no effect of the TFD on the bilayer structure. Further data modelling was performed by treating the structure factor $S(Q)$ according to the Modified Caillé Theory [32], while the total scattering intensity $I(Q)$ was modeled according to Equation 1:

$$I(Q) = \frac{(1-N_{diff})S(Q)P(Q)+N_{diff}P(Q)}{Q^2} \quad \text{Eq. 1}$$

which is a linear combination of the contributions $S(Q)$ and $P(Q)$ (form factor) weighed on the fraction N_{diff} of positionally uncorrelated bilayers (*i.e.*, unilamellar vesicles). The electron density of the lipid bilayer was modeled using three-Gaussian profiles [33]: two Gaussians represent the headgroups, centered at z_H , and one Gaussian is used to represent the terminal $-CH_3$ group at the bilayer's center. The procedure allowed us to determine the center z_H and the width σ_H of the Gaussians representing the headgroups, and to calculate the bilayer thickness (*i.e.* the headgroup-to-headgroup thickness of the lipid double-layer) as:

$$d_B = 2(z_H + 2\sigma_H) \quad \text{Eq. 2}$$

The salient structural features of a model bilayer, along with a typical electron density profile ($\rho(z)$ as a function of the distance z from the bilayer center) are represented in Scheme 3, while fit results for the patterns in Figure 2 are displayed in Table 2.

Scheme 3. Pictorial representation of a model lipid bilayer and the corresponding electron density profile, where: d = lamellar spacing; d_w (Å): thickness of water layer between headgroups (MLV only); d_B (Å): bilayer thickness; d_H (Å): headgroup thickness; d_C (Å): half thickness of hydrophobic region; z_H (Å) and σ_H (Å): center and width, respectively, of the Gaussians representing the headgroups.

<i>Parameter</i>	a	b	c	d
d (Å)	62.82 (±0.01)	62.75 (±0.01)	N/A	N/A
z_H (Å)	19.4 (±0.2)	20.0 (±0.1)	17.5 (±0.1)	17.6 (±0.1)
σ_H (Å)	3 *	3 *	3 *	3 *
N_{diff}	0	0	1	1
<i>N. of lamellae</i>	25 (±1)	26 (±1)	N/A	N/A
d_B (Å)	51 (±1)	52 (±1)	47 (±1)	47 (±1)
d_w (Å)	12 (±1)	11 (±1)	N/A	N/A

Table 2. Results of SAXS data modelling (Figure 2) and calculation of some structural properties. d (Å): lamellar spacing; z_H (Å) and σ_H (Å): center and width, respectively, of the Gaussians representing the headgroups; N_{diff} : ratio of non-interacting bilayers (*i.e.* ULVs); *N. of lamellae*: average number of interacting lamellae; d_B (Å): bilayer thickness; d_w (Å): thickness of inter-lamellar water space. N/A = not applicable; * = constrained parameter.

For the POPC/DOPE system, we determined $d_B = 51$ Å without TFD and $d_B = 52$ Å with TFD. Assuming the average headgroup thickness to be the weighted average of the phosphatidylcholine and phosphatidylethanolamine headgroups [34], $d_H = 8.9$ Å, through an elementary geometric deduction (Scheme 1) we obtain for half the hydrophobic region $d_C \approx 16$ Å. This value is comparable to what reported in the literature for POPC bilayers at 2 °C [35], nevertheless, our calculated d_C pertains to samples at 25 °C and is likely due to presence of 30% DOPE in the bilayer. However, care must be taken when dealing with SAXS patterns where less than four Bragg peaks

are present, as the resolution of the electron density profile is low [36] and it is not always possible to discern the exact threshold between headgroup and tail Gaussians.

The spectra pertaining to the samples containing also 12-bis-THA, with and without TFD (Figure 2C,D), are both consistent with the pure form factor $P(Q)$ of non-interacting lipid bilayers, *i.e.* only unilamellar vesicles are present. These form spontaneously upon incorporation of 12-bis-THA in the bilayer due to the positive charges of the bolaamphiphile molecules [37], as the bilayer bends in order to minimize repulsion between neighbouring headgroups, and the formation of MLVs is hindered by strong electrostatic repulsion between neighbouring bilayers. Interestingly, there is no trace of liquid-crystalline phases in the POPC/DOPE/12-bis-THA/TFD system. Evidently, the 12-bis-THA/TFD charge ratio used in this instance is too high to induce the formation of lipoplexes in columnar liquid-crystalline phases. Therefore, we can hypothesize that the reason for the observed loss of material during MLV extrusion could be the affinity of the 12-bis-THA/TFD complex for polycarbonate membranes. Indeed, in some experiments 12-bis-THA iodide (which is poorly water soluble; data not shown) has shown a marked tendency to adsorb on polycarbonate filters; the charge-neutralized complex with TFD might possess a similar affinity for the extrusion filters due to hydrophobic interactions. Another possible reason could be an increased permeability of the vesicles due to a detergency effect of 12-bis-THA, although preliminary studies involving the interaction of the bolaamphiphile with DPPC bilayers (unpublished) have shown that detergency should take place for higher 12-bis-THA concentrations than those used in the present work.

Eventually, we tackled this issue by turning to the surface decoration method. POPC- and POPC/DOPE dry films were hydrated with a TFD solution to increase the chance of encapsulating part of the DNA in the liposomal cores. After extrusion, 12-bis-THA was taken up from a dry film onto the pre-formed liposomes. ζ -potential measurements were positive whenever 12-bis-THA was included, even in the presence of the TFD (positive-to-negative charge ratio $Z_{+/-} = 22$), and repeated DLS analysis showed no variation in either size, polydispersity index, or scattering

intensity of POPC and POPC/DOPE liposomes over at least three months (data not shown), attesting the high colloidal stability of these systems. Dilution of the formulations in saline NaCl 150 mM did not lead to turbidity or precipitation. Therefore, both types of liposomes appear compatible, for size and surface charge as well as for their stability in time, with the desired application as gene delivery vectors.

At this point, since the bolaamphiphile is in large excess compared to the oligonucleotide, one could argue that the addition of 12-bis-THA to the preformed liposomes in a TFD solution might lead to the formation of free TFD/12-bis-THA nanoplexes in the bulk solvent (Scheme 4, scenario b).

Scheme 4. Schematic illustration of possible scenarios unfolding upon addition of 12-bis-THA to POPC/DOPE liposomes in a TFD solution. (a) 12-bis-THA adsorbs onto the lipid bilayer and attracts the TFD by electrostatic interaction. (b) 12-bis-THA preferentially forms isolated nanoplexes with the TFD in the bulk solution.

In order to confirm the localization of the TFD at the positively charged liposomal surface (scenario *a* in Scheme 4), the nanoscale structure of POPC/DOPE/12-bis-THA liposomes containing growing amounts of TFD was investigated by means of synchrotron SAXS. The spectra recorded for the systems with 0, 10, and 20 $\mu\text{g/mL}$ TFD are shown in Figure 3 along with the respective best model fits obtained with Equation 1.

Figure 3. SAXS patterns obtained for POPC/DOPE/12-bis-THA liposomes containing growing concentrations of TFD. Experimental data are represented with markers, while model curves are represented by lines.

The spectra are all similar and they show both a structure factor and a form factor. This suggests the presence of residual oligolamellar vesicles (OLV), where the bilayers are in interaction with each other: OLV contribute greatly to the scattered radiation even when they are present in very small numbers. Only two Bragg reflections are observed, due to bilayer disorder originating from bending fluctuation in the fluid L_α phase (third kind- or Caillé disorder) [36]. For the liposomes with no TFD, the fit results presented in Table 3 indicate that the SAXS pattern is consistent with a maximum number of 2 interacting lamellae; such bi-lamellar vesicles are present in very low number, since the contribution of the diffuse scattering is $N_{diff} = 97\%$ of the total $I(Q)$. The bilayer thickness calculated with Equation 2 is $d_B = 48 \text{ \AA}$, in agreement with previous results (Table 2).

<i>Parameter</i>	[TFD]	[TFD]	[TFD]
	0 $\mu\text{g/mL}$	10 $\mu\text{g/mL}$	20 $\mu\text{g/mL}$
$d \text{ (\AA)}$	64.9 (± 0.2)	64.3 (± 0.1)	62.0 (± 0.2)
$z_H \text{ (\AA)}$	17.79 (± 0.06)	18.4 (± 0.4)	15.93 (± 0.07)
$\sigma_H \text{ (\AA)}$	2.996 (± 0.004)	3.2 (± 0.4)	3 (± 1)
N_{diff}	0.972 (± 0.001)	0.9638 (± 0.0008)	0.969 (± 0.001)
<i>N. of lamellae</i>	2.000 (± 0.000)	2 *	2 *
$d_B \text{ (\AA)}$	48 (± 1)	50 (± 1)	N/A

Table 3. Results of SAXS data modelling of the samples of Figure 3 with GAP software and calculation of some structural properties. d (Å): lamellar spacing; z_H (Å) and σ_H (Å): center and width, respectively, of the Gaussians representing the headgroups; N_{diff} : ratio of uninteracting bilayers (*i.e.* ULVs); N : of lamellae: average number of interacting lamellae; d_B (Å): bilayer thickness. * = constrained parameter.

In liposomes with 10 $\mu\text{g/mL}$ TFD, the quality of the fitting was slightly poorer than for the spectrum of neat POPC/DOPE/12-bis-THA liposomes. Here, the number of interacting lamellae was constrained to 2 during the fitting procedure. The bilayer thickness obtained from the electron density profiles was 50 Å, which is 2 Å larger than the value obtained for the sample without TFD. At $[\text{TFD}] = 20 \mu\text{g/mL}$, data modelling with Equation 1 fails, most probably due to this model being unable to account for bilayer asymmetry. Such asymmetry between outer and inner lipid leaflets is suggested by the non-zero second node in the experimental scattering pattern [38], and can be explained by considering that the TFD molecules can only interact by charge compensation with the 12-bis-THA adsorbed on the outer liposomal leaflet. With growing TFD concentration, this effect becomes more evident as more oligonucleotide accumulates at the surface. For this reason the scattering curves for the samples with $[\text{TFD}] = 0$ and 10 $\mu\text{g/mL}$ can still be fitted using the model of Equation 1, but not the one with $[\text{TFD}] = 20 \mu\text{g/mL}$. This result supports the scenario in which no 12-bis-THA/TFD nanoplexes are formed in the bulk solution. This hypothesis is further reinforced by the fact that, upon dilution of the formulations in saline media, no turbidity or precipitation occur (data not shown). Indeed, since the nanoplexes are unstable in such media, as shown in the first part of this work, the absence of precipitate can safely be taken as proof that no free nanoplexes are present in the bulk solution of the liposomal formulations.

Liposomes decorated with 12-bis-THA were also loaded with a fluorescently (green) labelled TFD and challenged against a standard laboratory *E. coli* strain, where the bacterial membrane was labelled with a red fluorophore. The samples were imaged by means of confocal laser scanning

microscopy (CLSM); at least 10 different fields of view were evaluated, with a total number of analyzed bacteria cells of approximately 5000. The detection limits of our CLSM experiments demanded the incubation of bacterial cells with relatively high concentrations of liposome suspensions, in the order of 2.65 mmol/L total lipids, corresponding to 90 μ M of 12-bis-THA.

In the case of the POPC/12-bis-THA/TFD systems, images (Figure 4a,b) clearly show an interaction with the bacterial membranes, with evident accumulation of green fluorescent material at the poles and the septa of the bacteria. These are the areas of the *E. coli* membrane especially rich in cardiolipin [39], a doubly-anionic lipid that is also present at high concentrations in the mitochondrial membrane of eukaryotic cells [40]. This result is in agreement with research involving the interaction of 12-bis-THA with model membranes [17] and the use of dequalinium as an efficient targeting system for mitochondria [41]. Moreover, a recent paper has demonstrated the key role of cardiolipin in the binding of cationic antimicrobial peptides and the perturbation of model bacterial membranes [42], which strengthens even more the idea that the affinity of certain cationic antimicrobials for cardiolipin could be exploited as an active targeting mechanism. However, the TFD release and delivery efficiency to the *E. coli* cytoplasm was low for POPC/12-bis-THA/TFD liposomes, with less than 2% of the visualized cells presenting a diffuse intracellular green signal compatible with intracellular TFD release.

Figure 4. Confocal microscopy images of the interaction between liposomes loaded with a fluorescent TFD (green) and *E. coli* bacteria (red). Separate channels and combined channels displayed. (a) and (b) POPC/12-bis-THA/TFD liposomes; (c) and (d) POPC/DOPE/12-bis-THA/TFD liposomes.

The situation is rather different for POPC/DOPE liposomes: Figure 4c,d clearly show a diffuse green fluorescence in the bacterial cytoplasm, confirming the effective delivery of the TFD across

the *E. coli* membrane. This hints at the fundamental role of DOPE in promoting the fusion of liposomal bilayers with bacterial membranes, leading to the release of the TFD in the cytoplasm. Therefore, the fusogenic DOPE lipid is a key component for maximized delivery of the TFD nanoplexes to the bacterial cell. A possible explanation may lie in the fact that the *E. coli* inner membrane is composed of > 80% phosphatidylethanolamine lipids [43,44].

Biological evaluation of liposomes

Liposomes based on the POPC/DOPE mixture were tested for their biological properties of interest, namely antibacterial activity and toxicity, *in vitro* and *in vivo*. To determine the activity of liposomal formulations on bacterial membranes a standard bacterial growth assay was used against the model *Escherichia coli*. As reported in Table 4, both POPC/DOPE/12-bis-THA and POPC/DOPE/12-bis-THA/TFD liposomes showed similar antibacterial activity of 1.1 $\mu\text{mol/L}$ (with reference to 12-bis-THA, see Figure S3 for corresponding growth curves), which compares with that of the bare nanoplex [17]. Hence, despite the differences seen in the CLSM results concerning the efficacy of delivery for the two formulations (Figure 4), the membrane activity of the formulations was correlated to the concentration of 12-bis-THA.

The cytotoxicity of liposomal formulations was evaluated by measuring IC_{50} values with the MTT assay on Caco-2 intestinal epithelial cells (Table 4). Liposomes devoid of 12-bis-THA inflicted no measurable cytotoxicity up to a concentration of ~ 0.5 mM total lipids. For POPC/DOPE/12-bis-THA and POPC/DOPE/12-bis-THA/TFD liposomes the values of IC_{50} were 34 μM and 32 μM , respectively. The concentration of total lipids at these IC_{50} concentrations would be consistent with the 20:1 ratio of lipid:12-bis-THA, *i.e.* 680 and 640 μM , respectively. IC_{50} values were comparable to the values gained for other transfection agents [45–47] and approximately two-fold lower than that recorded for TFD/12-bis-THA nanoplexes [17]. The combination of improved colloidal stability of 12-bis-THA liposome formulations (*cf.* nanoplexes) and the presence of fusogenic DOPE increases the association with Caco-2 cells, as indicated by

flow cytometry analysis (Figure S5) with the likely consequence of increased membrane binding and subsequent intracellular penetration.

Samples	12-bis-THA	12-bis-THA
	MIC ($\mu\text{mol/L}$)	IC ₅₀ ($\mu\text{mol/L}$)
POPC/DOPE	--	ND
POPC/DOPE/TFD	--	ND
POPC/DOPE/12-bis-THA/TFD	1.1	33.9 (\pm 1.4)
POPC/DOPE/12-bis-THA	1.1	31.8 (\pm 3.1)

Table 4. Biological evaluation of liposomes in antibacterial activity (MIC) against *E. coli* and cytotoxicity (IC₅₀) in Caco-2 cells after 24 h exposure. ND: no observable toxicity at concentrations tested. Data are mean \pm standard deviations.

In order to extend the toxicity profile of these formulations, the toxicity of the liposomal formulations was also assessed using the *Xenopus laevis* embryo model. This model can help to bridge the gap between traditional *in vitro* and preclinical mammalian assays in biomedical research and drug development. Animal models to be employed for organism-based chemical screens have to be small, low-cost and compatible with simple culture conditions to be suitable for high-throughput screening [27]. *Xenopus* meets these requirements as its fertilization and embryonic development is external and they produce a large number of transparent embryos that are small enough to be placed in 48- or 96-well plates.

The cumulative survival of the embryos after 96 h exposure with the liposomes is summarized in Figure 5. Liposomes containing no 12-bis-THA did not cause any toxicity to the larvae even after incubation at the highest dose (2.65 mM lipids). As seen with the eukaryotic cell model, the addition of 12-bis-THA into the liposomes strongly increased the formulation toxicity but no differences were observed between the 12-bis-THA-loaded liposomes and the 12-bis-THA-

loaded liposomes with TFDs. Both of these 12-bis-THA-loaded liposomes display toxic potential in this animal model at the specific incubation conditions used (stage 38 to 45) above 5.6 μM 12-bis-THA (0.16 mM lipids), a value in the same range as the IC₅₀ values obtained for Caco-2 cell line (Table 4) confirming a good correlation between the eukaryotic and the *Xenopus laevis* model. The dynamics of the different liposome toxicity and the morphology of the surviving embryos (at stage 45) are reported as Supporting Information (Figure S6). Representative images show that the surviving embryos had no pattern of malformation or any visible phenotype related to toxicity (oedema, lack of pigmentation, bent spine, etc.) [48]. In summary these biological data indicate that the liposomal formulations retain antimicrobial activity and maintain a favourable *in vitro* activity-to-toxicity ratio (therapeutic index) [49] whilst improving the pharmaceutical properties of the nanoplexes.

Figure 5. *Xenopus laevis* nanotoxicity assay. *Xenopus laevis* larvae survival after exposure to different liposome formulations from stage 38 to stage 45 at 18 °C. Histograms shown are of 30 embryos at each concentration. Data are mean \pm S.D.

4. Conclusions

Innovative approaches are needed to curtail antimicrobial resistance. TFDs are being developed as oligonucleotide antimicrobials to combat antibiotic resistance and a nanostructured formulation with 12-bis-THA has been shown to be efficacious in several models. In order to improve their stability, we have created liposomal formulations by decorating the surface of POPC and POPC/DOPE liposomes with 12-bis-THA, and exploited its ability to complex oligonucleotides to load a model TFD onto the lipid scaffolds. Confocal microscopy imaging was used to assess the ability of liposomes containing fluorescently labelled TFDs to transfect *E. coli* cells. In the case of the POPC formulations, images evidenced an interaction of liposomes with the bacterial membrane areas richer in cardiolipin, reinforcing the role of this negative lipid in the targeting for 12-bis-THA, like other cationic antimicrobials, towards bacteria. However only POPC/DOPE liposomes effectively delivered the TFD to the *E. coli* cytoplasm, evidencing the requirement of a fusogenic helper lipid to successfully cross the bacterial membrane and boost transfection. POPC/DOPE liposomes therefore appear extremely promising as vector for the delivery of this new generation of antibacterial drugs. Preliminary biological assays demonstrated a non-negligible cytotoxic effect of 12-bis-THA towards human Caco-2 cells: future work will focus on the reduction of cytotoxicity by modulating the concentration of 12-bis-THA through its partial replacement with more biocompatible cationic lipids.

Acknowledgements

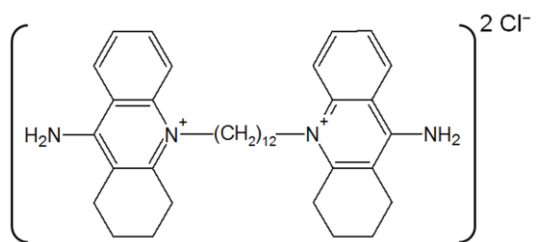
This work was funded under the 7-People Framework – Marie Curie Industry and Academia Partnerships & Pathways scheme (grant agreement nr. 612338). We gratefully acknowledge technical assistance from: Mrs. Ghislaine Frébourg (Cryo-TEM; Institut de Biologie Paris-Seine, Université Pierre et Marie Curie, Paris, France); Dr. Paolo Tempesti (in-house SAXS; CSGI and Department of Chemistry, University of Florence, Italy); Dr. Heinz Amenitsch (synchrotron SAXS; Elettra, Trieste, Italy). The authors thank Prof. Alessio Mengoni (Department of Biology, University of Florence, Italy) for providing *E. coli* for CLSM imaging; Prof. Georg Pabst (University of Graz, Austria) for providing the GAP software free of charge; Dr. Alejandro Marin-Menendez and Dr. Gladys Ruiz Estrada for collaboration in some of the experiments.

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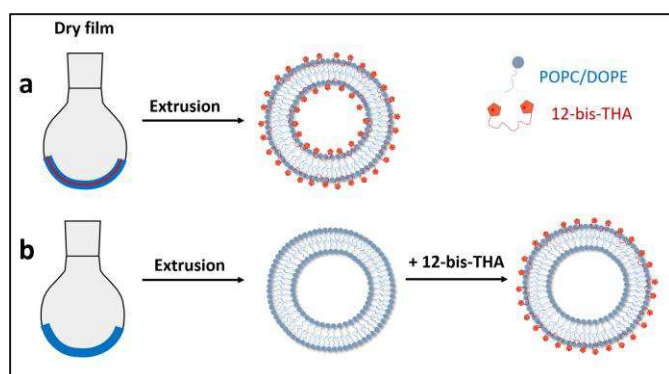
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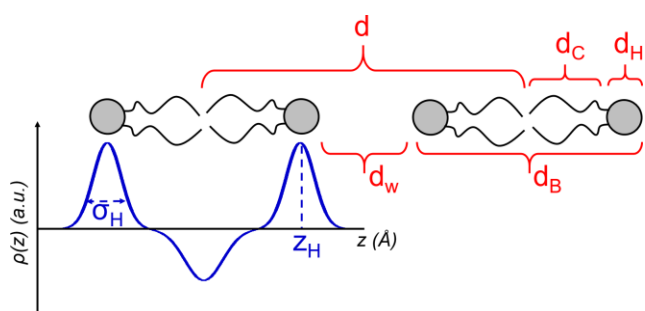
Scheme 1

ACCEPTED MANUSCRIPT



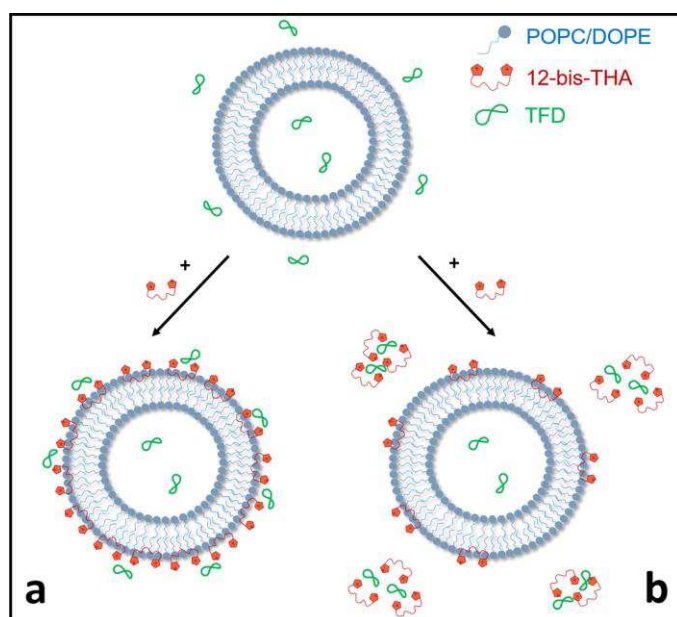
Scheme 2

ACCEPTED MANUSCRIPT



Scheme 3

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Scheme 4

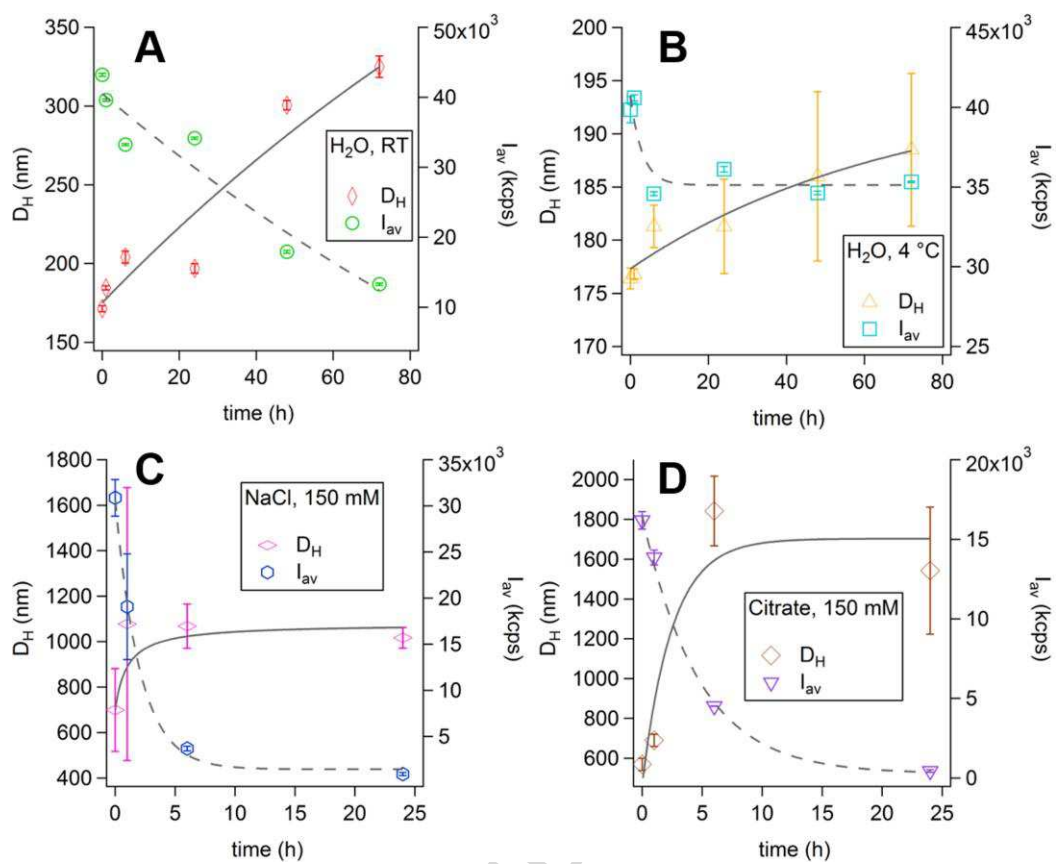


Fig. 1

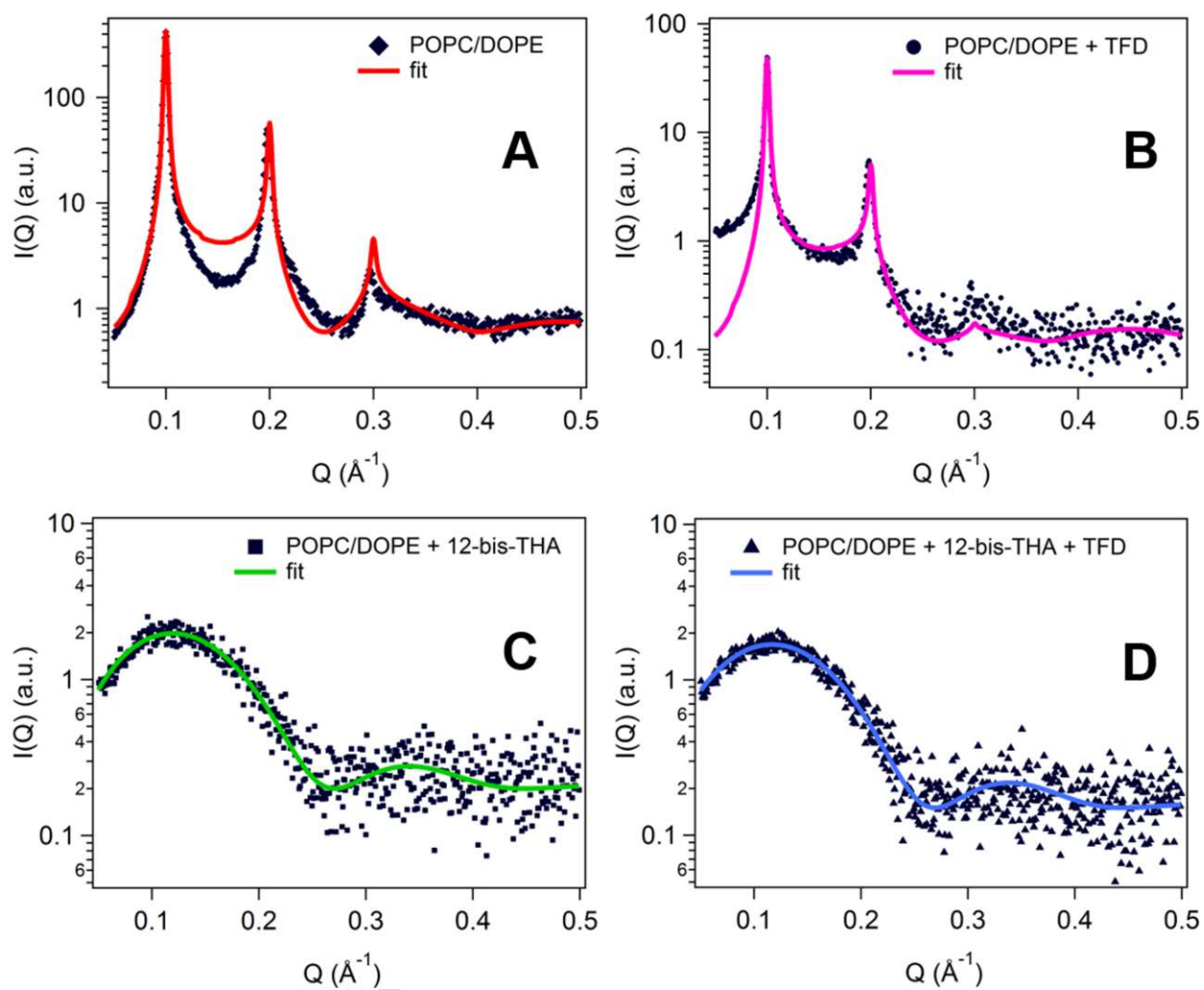


Fig. 2

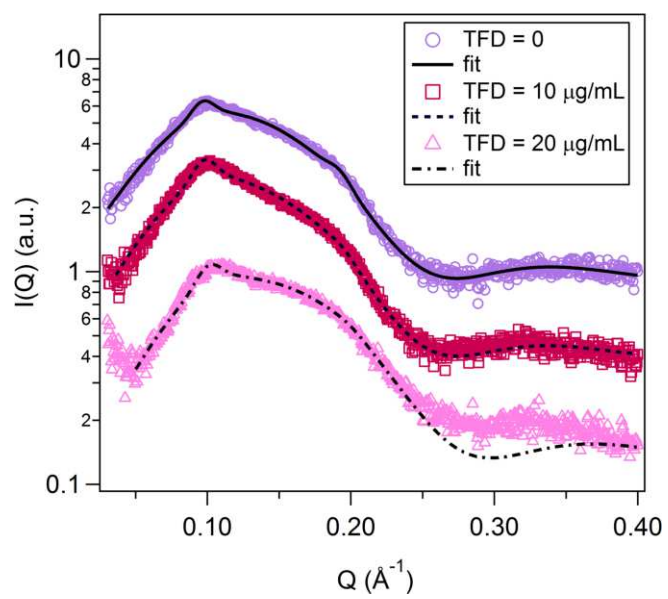


Fig. 3

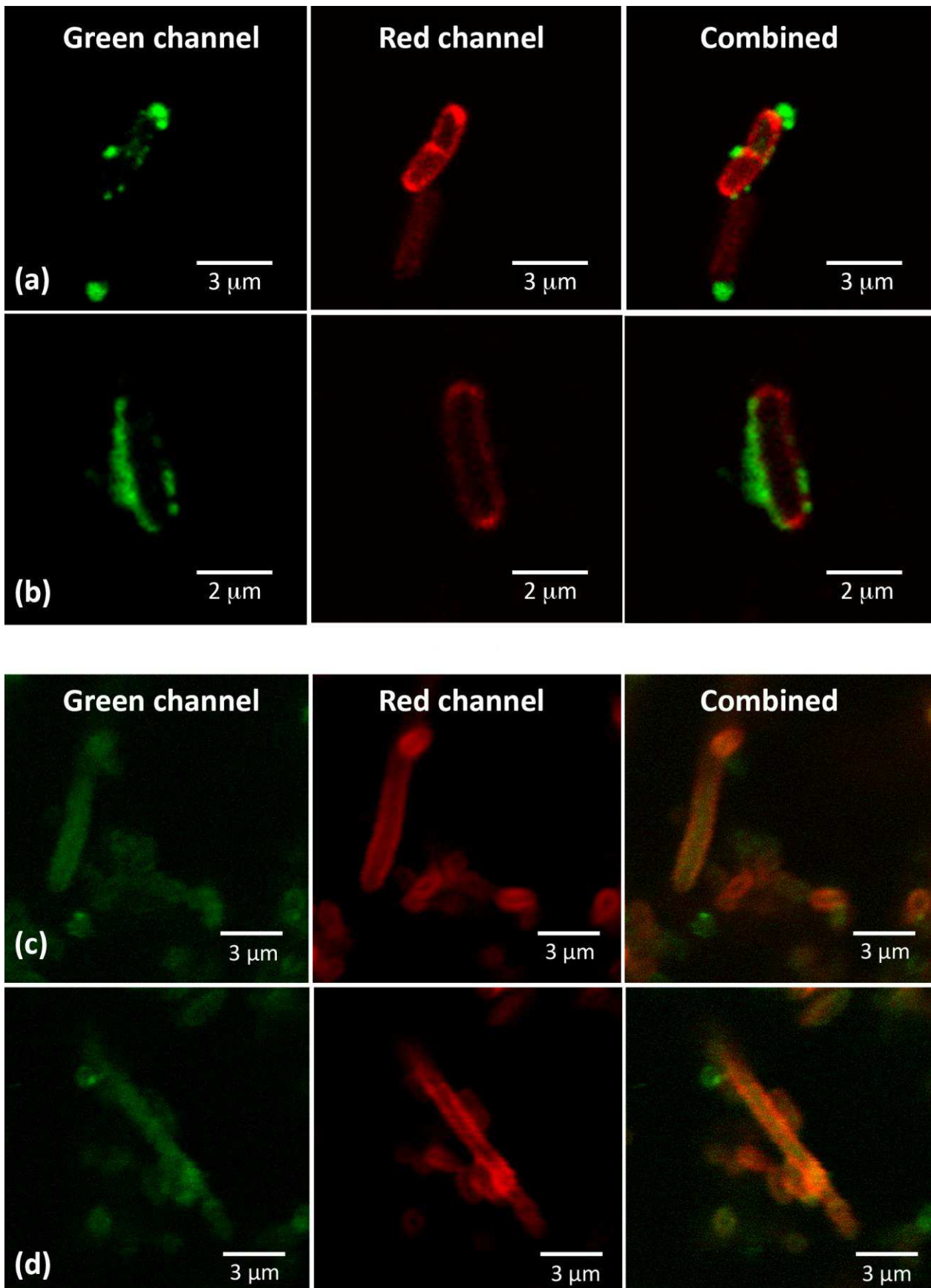


Fig. 4

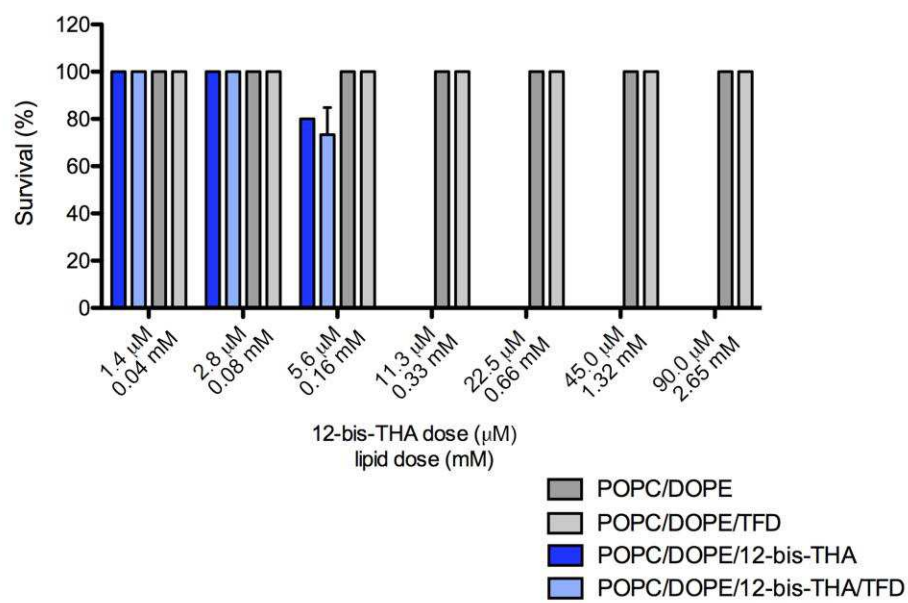
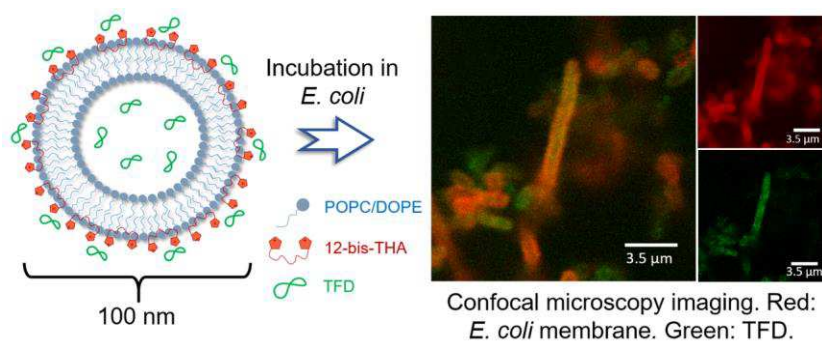


Fig. 5



Graphical abstract

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Highlights

- A liposomal formulation is developed for antibacterial complex
- The physical-chemical features of the liposomes are investigated
- The delivery of the antibacterial oligonucleotide is assessed in *E. coli*

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