

# Enhanced Intra-Liposomal Metallic Nanoparticle Payload Capacity Using Microfluidics Assisted Self-Assembly

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**Abstract**

Hybrids composed of liposomes (L) and metallic nanoparticles (NP) hold great potential for imaging and drug delivery purposes. However, the efficient incorporation of metallic nanoparticles into liposomes using conventional methodologies has so far proved to be challenging. In this study, we report the fabrication of hybrids of liposomes and hydrophobic gold nanoparticles of size 2-4 nm (Au) using a microfluidic assisted self-assembly process. The incorporation of increasing amounts of Au nanoparticles into liposomes was examined using microfluidics and compared to L-AuNP hybrids prepared by the reverse-phase evaporation method. Our microfluidics strategy produced L-AuNP hybrids with a homogeneous size distribution, smaller polydispersity index, and a 3-fold increase in loading efficiency when compared to those hybrids prepared using the reverse-phase method of production. Quantification of the loading efficiency was determined by ultraviolet spectroscopy, inductively coupled plasma mass spectroscopy and centrifugal field flow fractionation and confirmed qualitatively by transmission electron microscopy. The higher loading of gold nanoparticles into the liposomes achieved using microfluidics produced a slightly thicker and more rigid bilayer as determined with small angle neutron scattering. These observations were confirmed using fluorescent anisotropy and atomic force microscopy, respectively. Structural characterization of the liposomal-nanoparticle hybrids with cryo-electron microscopy revealed the co-existence of membrane-embedded and interdigitated nanoparticle-rich domains suggesting AuNP incorporation through hydrophobic interactions. The microfluidic technique that we describe in this study allows for the automated production of monodisperse liposomal-nanoparticle hybrids with high loading capacity highlighting the utility of microfluidics to improve the payload of metallic nanoparticles within liposomes, thereby enhancing their application for imaging and drug delivery.

## Introduction

Since their discovery in 1965, liposomes have been widely investigated for various therapeutic and imaging applications and are approved for the treatment of several clinical conditions in particular for cancer and inflammatory conditions<sup>1, 2</sup>. Liposomes are formed by self-assembly of phospholipid molecules into vesicles that can effectively encapsulate hydrophilic drugs in their aqueous core<sup>3, 4</sup> and/or incorporate compounds into their lipid membrane<sup>4, 5, 6</sup>. Other advantages that liposomes offer include biocompatibility, biodegradability, modification of blood circulation time and thereby the pharmacokinetic profile of encapsulated drugs mainly through surface modification with PEGylated lipids (i.e. Stealth liposomes)<sup>7</sup>. As a consequence of these properties, it is possible to achieve the selective (passive) delivery of liposomes through malformed blood vessels at the disease site (e.g. into a tumour) while at the same time ensuring minimum accumulation into healthy tissues<sup>8, 9</sup>, in this manner the safety profile of liposomally-encapsulated drugs, such as doxorubicin, can be significantly improved.

In addition to the development of liposomes for therapeutic purposes, the engineering of liposomal-metallic nanoparticles hybrids has also attracted considerable interest for imaging, photo-thermal and theranostic (i.e. the combining of imaging/diagnosis and therapy in one delivery system) applications. One example of the benefits of using gold nanoparticles (AuNPs) for imaging and photo-thermal applications is their surface plasmon resonance properties<sup>10</sup>. Specifically, AuNPs can absorb certain wavelengths of light resulting in the oscillation of surface electrons and subsequently producing a local heating effect. The intensity and duration of this effect can be altered by modifying the intensity and duration of the laser beam applied, as well as the concentration of AuNPs used<sup>11</sup>. Incorporating AuNPs into liposomes can improve their colloid stability as well as their biological performance<sup>12, 13, 14, 10, 15, 16, 17, 18, 19, 20</sup>. Indeed, it is well established that stimuli responsive liposomes can facilitate the site specific release of entrapped material in response to external light<sup>21, 22</sup>.

There are different methods of L-AuNP hybrid fabrication that have been reported by ourselves and others<sup>14, 23</sup>. These can be categorised into three depending on the location of metallic NPs relative to the liposomal membrane, namely a) the incorporation of small (< 5nm) hydrophobic NPs into the lipid membrane, b) encapsulation of hydrophilic NPs into the liposomal aqueous core, and c) surface adsorption or complexation mainly through electrostatic interaction or surface adsorption. Although several interesting examples of L-AuNP hybrids has been developed for either simple colloidal stabilisation<sup>14, 24</sup>, medical diagnosis<sup>25</sup> and stimuli-responsive applications<sup>26, 27, 28</sup>, the efficient incorporation of metallic NPs into the liposomes remains the main challenge in the use and application of these systems.

Microfluidics has emerged recently as a very promising technology for liposome fabrication. Compared to conventional liposome production methods, microfluidics offers precise control over liposome size and polydispersity<sup>29, 30</sup> and it is a very promising method for the preparation of lipid nanoparticles encapsulating macromolecules such as siRNA and mRNA<sup>31, 32, 33</sup>. Furthermore, this control is achieved in a single step without the need for additional post-production processing through extrusion or sonication. Very promising examples of liposomal systems with high payload capacity of hydrophilic and/or lipophilic drugs have been reported<sup>34, 35, 36, 37, 38</sup>. Moreover, advances in the design of integrated microfluidic devices allow the combination of in-line liposome fabrication with other processes such as remote drug loading<sup>39</sup>, and complexation with genetic material such as pDNA and siRNA<sup>40</sup>. Significantly, liposomes fabricated by microfluidics showed very similar or even

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3 improved physicochemical properties and biological functions (such as increased  
4 transfection efficiency<sup>40</sup> and greater drug loading/retention<sup>35, 39</sup> compared to  
5 liposomes prepared by traditional methods, while at the same time minimising the  
6 steps required during processing saving several hours or days of work<sup>39, 41</sup>. Here, we  
7 investigated the possibility of using microfluidics to encapsulate metallic nanoparticles  
8 in the liposomes for imaging applications or modulation of drug release properties  
9 when combined with therapeutic molecules.

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11 In this study we aim to improve the incorporation of metallic NPs into liposomes using  
12 a microfluidic assisted self-assembly process. For this purpose, hydrophobic AuNPs  
13 of size 2-4 nm were selected as model nanoparticles for incorporation into liposomes.  
14 The incorporation of increasing concentrations of AuNPs (0.025, 0.25 and 2.5 mg/mL)  
15 into liposomes (total lipid concentration is 4.5 mg/ml) were studied using microfluidic  
16 and directly compared to L-AuNP hybrids prepared by reverse-phase evaporation  
17 (REV) method. Physicochemical properties, encapsulation capacity, morphology of L-  
18 AuNP hybrids prepared by the two methods were compared. In addition, the effect of  
19 Au NPs incorporation on the lipid membrane rigidity and thickness was investigated.  
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## Experimental

### Materials

Hydrogenated soy phosphatidylcholine (HSPC) and 1,2-distearoyl-sn-glycero-3-phosphoethanolamine-N-[methoxy(polyethylene glycol)-2000] (DSPE-PEG<sub>2000</sub>) were kind gifts from Lipoid GmbH (Ludwigshafen, Germany). Chloroform and methanol were purchased from Fisher Scientific (Loughborough, UK). 1,6-diphenyl-1,3,5-hexatriene (DPH) was supplied from Invitrogen (Paisley, UK). Phosphate buffer saline (PBS), Sepharose CL-4B, 2 w/v% octanethiol-functionalized Au nanoparticles in toluene, diethyl ether, 8-anilino-1-naphthalenesulfonic acid (ANS), Aqua regia (HNO<sub>3</sub>:HCl 1:3 v/v) and tetrahydrofuran were all obtained from Sigma-Aldrich (Dorset, UK). MilliQ® water (Millipore Milli-Q, Watford, UK) was used throughout the study. D<sub>2</sub>O (> 99.9% purity) was purchased from Aldrich (Dorset, UK).

### Preparation of L-AuNP Hybrids by Microfluidics Method (MF)

L-AuNP hybrids were self-assembled using the automated microfluidic Asia 320 system (Syrris, Royston UK). First, a solution of Au nanoparticles in CHCl<sub>3</sub> was prepared by evaporating (BÜCHI, Switzerland) toluene in which Au nanoparticles were already dissolved and re-suspending the nanoparticles in CHCl<sub>3</sub>. Three different concentrations of Au nanoparticles dispersed in CHCl<sub>3</sub> (1mL) were then mixed with a 95:5 mol:mol solution of HSPC:DSPE-PEG<sub>2000</sub> (pre-dissolved in 1mL MeOH) as shown in Table 1.

**Table 1:** Theoretical Concentration of Au nanoparticles used for the preparation of L-AuNP hybrids.

Formulation designation	Total lipid concentration (mg/mL) HSPC:DSPE-PEG <sub>2000</sub> (95:5 mol:mol)	Au nanoparticles (AuNPs) (mg/mL)
L-AuNP 0.025	4.5	0.025
L-AuNP 0.25	4.5	0.25
L-AuNP 2.5	4.5	2.5

Following the mixing of the AuNPs with the lipids, CHCl<sub>3</sub> was evaporated using a rotary evaporator at 460 mbar for 20 min at 40°C. The resulting methanolic suspension of lipids and AuNPs was then further diluted with MeOH to a total lipid concentration of 1 mg/mL before introducing it into the Asia microfluidics system. Note that preliminary studies had showed that higher lipid concentrations than 1 mg/mL resulted in the production of larger sized liposomes. Once in the microfluidics set-up, the methanolic mixture containing both the lipids and the AuNPs was mixed with an aqueous solution (PBS, pH 7.4) in an Asia 26 µL micromixer reaction chip (Syrris part number: 2101411 - internal main channel cross section of 125x350 µm, internal mixing channel cross section of 50x125 µm). The optimum mixing conditions was determined by first exploring different flow rates such that an organic:aqueous flow rate ratio (FRR) of either 1:5 or 1:10 was used along with a total flow rate (TFR) of either 220, 330, 680, 1370 or 2750 µL/min (as described in Table 2). Optimisation was initially explored using plain ('empty') liposomes and finalised with L-AuNP systems.

Once prepared, L-AuNP hybrids were then dialysed for 24 h using a Spectra-Por® Float-A-Lyzer (MWCO of 10 kDa) against PBS in order to remove any residual methanol. Following dialysis, a concentration step was performed using centrifugal viva-spin column 20 to concentrate the final L-AuNP formulations to a total lipid concentration of 4.5 mg/mL as confirmed by the Stewart's assay<sup>42</sup>.

**Table 2:** Microfluidic Parameters Used in the Study.

Total Flow Rate (TFR) ( $\mu\text{L}/\text{mL}$ )	Organic:Aqueous Flow Rate Ratio (FRR)			
	Organic:Aqueous = 1:10		Organic:Aqueous = 1:5	
	Organic flow rate ( $\mu\text{L}/\text{mL}$ )	Aqueous flow rate ( $\mu\text{L}/\text{mL}$ )	Organic flow rate ( $\mu\text{L}/\text{mL}$ )	Aqueous flow rate ( $\mu\text{L}/\text{mL}$ )
220	20	200	45	175
330	30	300	65	265
680	60	620	135	545
1370	120	1250	275	1095
2750	250	2500	550	2200

### Preparation of L-AuNP Hybrids by the Reverse-Phase Evaporation Method

L-AuNP hybrids were prepared using reverse-phase evaporation (REV) methodology as previously described<sup>43</sup> using the same lipid composition and the same initial concentration of Au nanoparticles (i.e. 0.025, 0.25 & 2.5 mg/mL), denoted as L-AuNP 0.025, L-AuNP 0.25 and L-AuNP 2.5, respectively. In brief, the required amount of hydrophobic AuNP dispersion was first added to a round bottom flask. The organic solvent (toluene) in which the AuNPs were dispersed was then removed using rotary evaporation at 6 mbar and 40°C for 30 min. The lipid mixture of 95:5 molar ratio of HSPC:DSPE-PEG<sub>2000</sub>, dissolved in a 4:1 v/v mixture of chloroform:methanol, was then added and the organic solvent evaporated to form the lipid film containing the nanoparticles. The AuNP-containing lipid film was then re-dissolved in 6 mL of 1:1 v/v chloroform:diethylether. Following this step, 1.5 mL of PBS was added and the resultant mixture bath sonicated for 15 min at 40°C after which time the organic solvents were removed using rotary evaporation at 460 mbar and 40°C for 2 h. The large unilamellar liposomes (LUVs) formed by this process were then reduced in size by 30 min bath sonication at 60°C.

### Characterization of L-AuNP Hybrids

The apparent hydrodynamic radius and polydispersity index (PDI) of the liposomes were measured using Zetasizer Nano ZS (Malvern, Instruments, UK). Measurements were performed at 25°C, after dialysis against PBS of the L-AuNP hybrids prepared with microfluidics methodology.

### Quantification of lipids concentration by Stewart's assay

The concentration of lipid in the final products was assessed using the Stewart assay<sup>42</sup>. In brief liposome sample (20  $\mu\text{L}$ ) was mixed with Stewart's reagent (0.5 mL) and  $\text{CHCl}_3$  (1 mL). The resultant mixture was shaken for 20 sec and centrifuged at 13,793 RCF (Heraeus Biofuge 13) and the absorbance of the lipid containing  $\text{CHCl}_3$  layer was measured at 485 nm and compared to a standard curve prepared by plotting the absorbance at 485 nm versus lipid concentration in the range between 0.02-5 mg/mL.

### Quantification of AuNP Loading Efficiency by Ultra Violet Spectroscopy and Inductively Coupled Plasma Mass Spectrometry

The amount of Au, and by implication the amount of AuNPs loaded into the liposomes was quantified using both ultraviolet (UV) spectroscopy and mass spectrometry. The UV

absorbance of the Au was recorded on Cary 50 UV/VIS (Agilent Technologies, US) with the value of the maximum absorbance measured at 510 nm (after correction for any light scattering) being used to quantify the amount of Au present by comparison to a standard calibration curve. For inductively coupled plasma mass spectrometry (ICP-MS) measurements, samples were first dissolved in 1 mL of aqua regia followed by a brief mixing for 30 sec. 100  $\mu$ L of the sample in aqua regia was then diluted with Milli-Q<sup>®</sup> water up to 5 mL (thereby making an aqua regia concentration of 2% v/v) before performing ICP-MS (Agilent Technologies 7500 cx). L-AuNP hybrids loading efficiencies were then expressed as Au/lipid w/w %.

### Separation and Characterization of L-AuNP Hybrids Fractions from Plain Liposomes

In order to separate and quantify the fraction of L-AuNP hybrids from the empty or plain liposomes contained in each sample, a centrifugation step was applied. Specifically, samples of L-AuNP hybrids loaded with different concentrations of Au nanoparticles were centrifuged at room temperature for 2 h at 13,793 RCF (Biofuge 13). Characterization of L-AuNP hybrids fraction (assumed to be the sediment observed under the conditions of the test) and the unloaded empty liposomal fraction (assumed to remain suspended in the supernatant under the conditions of the test) was performed by measuring the ratio of AuNPs/lipids present in each fraction using a combination of UV spectroscopy and the Stewart's assay. Any differences in size and PDI between the nanoparticles present in the two fractions were also determined as described above.

### Centrifugal Field Flow Fractionation Measurements

Centrifugal field flow fractionation (C-FFF) measurements were performed using a CF2000 C-FFF system (Postnova Analytics, Landsberg, Germany) which was coupled online to 4 detection instruments, namely 1) a UV/Vis spectrometer at 500 nm (S3210, Laserchrom, Rochester, UK), 2) a multiangle laser light scatterer (MALLS, Viscotek SEC-MALS20, Malvern Instruments, Worcestershire, UK) equipped with a laser operating at 532 nm, 3) a refractometer (Optilab T-rEX, Wyatt Technology, Dernbach, Germany) equipped with a laser operating at 633 nm and 4) a dynamic light scatterer (DLS, Zetasizer Nano SZ, Malvern Instruments, Worcestershire, UK). The dimensions of the channel used were channel thickness,  $w = 237 \mu\text{m}$ , channel area = 100  $\text{cm}^2$ , void volume ( $V_0$ ) = 2.597 mL, radius of rotation ( $r$ ) = 10.01 cm (according to the manufacturer's specification).

In a typical experiment, 20  $\mu$ L of sample was loaded in the injector loop and the sample injected over 114 sec with a rotor speed equal of 4900 rpm. After 5 min relaxation time, the sample was then eluted in PBS at a rate of 0.5 mL/min. The method-wizard of the CF2000 control software (version 1.0.2.2, Postnova Analytics) was used for automatic decay field calculations. The rotor speed at each time point ( $RPM_t$ ) is expressed in equation 1:

$$RPM_t = RPM_0 \left[ \frac{t_1 - t_\alpha}{t - t_\alpha} \right]^4 \quad (\text{Eq. 1})$$

where  $RPM_0$  = starting rotor speed,  $t_1$  = length of time for which  $RPM_0$  is kept constant,  $t$  is the time expressed in minutes,  $t_\alpha$  is an arbitrary constant expressed in minutes that can be tuned in order to modulate the decay rate,  $t_{tot}$  = decay time (the total duration of the elution being  $t_{tot} + t_1$ ). All samples, except for the MF L-AuNP hybrids 2.5, were eluted using the following parameters:  $RPM_0 = 4900$ ,  $t_1 = 10$ ,  $t_\alpha = -21$  and  $t_{tot} = 49$ . In contrast, the MF L-AuNP hybrids 2.5 were eluted using parameters of  $RPM_0 = 4900$ ,  $t_1 = 7$ ,  $t_\alpha = -35$  and  $t_{tot} = 111$ .

The apparent hydrodynamic diameter (Z-average size) of the eluted particles was measured by DLS in flow mode and the resulting chromatogram was analysed using the DLS analysis tool of the Zetasizer Software (version 7.11, Malvern).

C-FFF allows the separation of particles based on mass and apparent hydrodynamic diameter ( $d_H$ )<sup>39</sup>. According to C-FFF theory, the force applied on a single particle ( $F$ ) can be expressed as described in equation 2:

$$F = \frac{\pi}{6} d_H^3 \Delta\rho G \quad (\text{Eq. 2})$$

where  $\Delta\rho$  is the difference in apparent density between L-AuNPs and the solvent in which they are dispersed and  $G$ , the gravitational acceleration is defined as in equation 3;

$$G = \left( \frac{2\pi \cdot RPM_t}{60} \right)^2 r \quad (\text{Eq. 3})$$

The retention time ( $t_r$ ) is proportional to the force  $F$  according to equation 4:

$$t_r = \frac{FwV_0}{6kT\dot{V}} \quad (\text{Eq. 4})$$

where  $w$  = channel thickness,  $V_0$  = void volume,  $k$  = Boltzmann coefficient,  $T$  = absolute temperature and  $\dot{V}$  = channel flow rate.  $|\Delta\rho|$  for each time point can, therefore, be determined from a knowledge of the parameters  $r$ ,  $V_0$  and  $w$ , the method used for the elution ( $RPM_t$  and  $\dot{V}$ ) and the apparent hydrodynamic size of the particles determined during elution.

### Transmission Electron Microscopy and Scanning Transmission Electron Microscopy Studies

Transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) studies were performed by depositing 10  $\mu\text{L}$  of L-AuNP hybrid dispersion onto a carbon coated grid and staining with 1% w/v uranyl acetate solution. Excess liquid was removed by drying with a wick of filter paper and leaving the grids dry for 10 min. TEM images were acquired on a FEI (US) Tecnai 12 Biotwin Transmission Electron Microscope. Images were acquired with Gatan Orius SC1000 CCD camera. STEM imaging was carried out using a FEI (US) Titan G2 80-200 TEM microscope fitted with a probe side aberration corrector, a high brightness X-FEG electron source and operating at 200 kV.

X-rays energy dispersive spectroscopic (XEDS) measurements were performed on the FEI Titan microscope using the FEI SuperX system ( $\approx 0.7$  sR collection angle) with a probe current of 360 pA. High-angle annular dark-field (HAADF) images were acquired using an inner collection angle of 62 mrad and a probe convergence angle of 21 mrad. Processing the XEDS dataset were performed with the HyperSpy software<sup>44</sup>. Principal component analysis was used to denoise the hyperspectral datasets with 3 to 4 components being used to reconstruct the data. The Au and Uranium (U) elemental maps were obtained by integration of signal in the L lines at 9.71 keV and 13.61 keV, respectively.

### Cryo-Transmission Electron Microscopy

Visualization of the samples with cryo-transmission electron microscopy (Cryo-TEM) was performed to study the morphology of L-AuNP hybrids and to confirm the incorporation of metallic nanoparticles. Samples were vitrified by applying a 3  $\mu\text{L}$  aliquot to a previously glow-discharged 200-mesh hole and Quantifoil carbon grids (Ted Pella, USA). Grids were blotted and then plunged into liquid ethane using a FEI Vitrobot Mark IV (FEI Company, the Netherlands). The samples were imaged in bright field transmission electron microscopy (TEM) using a Tecnai G2F20 microscope (FEI Company, the Netherlands) equipped with a Schottky Field Emission electron source, a US1000 2kx2k Gatan CCD camera and operating at an acceleration voltage of 200 kV. The cryo-tomographic (CET) tilt series were collected on the vitrified sample by tilting over  $\pm 60^\circ$  in  $2^\circ$  steps. Computation of tomograms and post-processing were performed using the IMOD 4.9.2 software package<sup>45</sup>. Segmentation by isosurface and 3D visualization were undertaken using the Amira package (FEI Visualization Science Group, Bordeaux). Cryo-TEM and CET imaging were both



performed under low dose conditions, with a total dose of 60-80 electrons/Å<sup>2</sup> being used for the whole tilt series.

### Fluorescence Anisotropy Measurements

Fluorescence anisotropy experiments were performed to study the effect of metallic nanoparticles incorporation on the liposome's membrane fluidity. The hydrophobic probe, 1,6-diphenyl-1,3,5-hexatriene (DPH) and the hydrophilic probe, 8-anilino-1-naphthalenesulfonic acid (ANS) were used to monitor the changes in the fluidity of the hydrophobic region of the lipid membrane and near the liposome's surface, respectively. Experiments were performed as previously described<sup>46</sup>. Briefly, L-AuNP hybrids were further diluted to a total lipid of 0.025 mM total and divided into two 4 mL aliquots. Either a DPH in tetrahydrofuran solution (0.8 mM, 2.5 μL) or an aqueous ANS solution (10 mM, 4 μL) was mixed with the liposomes at 500:1 total lipid/DPH or 25:1 total lipid/ANS. To allow the probes to be incorporated, the samples were shaken at room temperature for 2 h and then left overnight before starting the measurements. Fluorescence polarization was then measured by a Carry Eclipse, Agilent technology equipped with automated polarizer and thermostatic cell holder connected to a water bath to control the sample temperature. For the experiments utilising DPH, the anisotropy measurements were performed using an excitation wavelength of 395 nm (slit of 10 nm) and emission wavelength of 476 nm (slit of 5 nm). Measurements were started at 25 °C, and then the temperature was increased gradually up to 65°C at a step change of 3°C. The samples were equilibrated for at least 2 min after each temperature change. Fluorescence anisotropy was then measured automatically by the spectrofluorometer using equation 5;

$$r = \frac{I_{V_V} - GI_{V_H}}{I_{V_V} + 2GI_{V_H}} \quad (\text{eq. 5})$$

where  $r$  = fluorescence anisotropy and  $I_{V_V}$  and  $I_{V_H}$  = the emission intensity excited with vertically polarized light and measured with emission polarizer oriented in a parallel or perpendicular direction to the plane of excitation, respectively.  $G$  = an instrument specific factor calculated to correct the instrument polarization, which is equal to  $I_{H_V}/I_{H_H}$ , and obtained by measuring the vertically and horizontally polarized emission intensities after excitation with horizontally polarized light. A sigmoidal Boltzmann curve was fitted to the experimental values were performed using Origin 8.5 software.

### Small Angle Neutron Scattering Measurements

Small angle neutron scattering (SANS) measurements on vesicles (prepared using the REV methodology) without a NP payload and L-AuNP hybrids prepared by both MF and REV methodology were performed using the beam line, SANS2D, at the ISIS pulsed neutron source (STFC Rutherford-Appleton Laboratory, Didcot, UK). All samples were prepared in PBS and diluted before measurement with an equal volume of PBS in deuterium oxide (D<sub>2</sub>O) in order to provide the contrast (or scattering length density difference) necessary for the SANS measurements. The empty lipid vesicles and the L-AuNP hybrids were measured at total lipid concentration of 0.5 mg/mL in 1 mL bango cells using a solvent of composition of 1:1 v/v PBS<sub>H2O</sub>:PBS<sub>D2O</sub> and at 25°C. Note that, with the exception of D<sub>2</sub>O, all the components using to make PBS<sub>D2O</sub> were protiated.

The SANS intensity,  $I(Q)$ , of the samples were measured as a function of the scattering vector as described in equation 6,

$$Q = (4\pi/\lambda)\sin(\theta/2) \quad (\text{eq. 6})$$

where  $\theta/2$  = the scattering angle. The data were normalised to the appropriate sample transmission after subtraction of the scattering of the relevant solvent which was normalised to its corresponding transmission. The fitting of the SANS data always included a flat background correction to allow for any mismatch in the incoherent and inelastic scattering

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3 between the sample and the solvent, with the levels of the fitted background being checked  
4 to ensure that they were physically reasonable. The SANS data obtained in the present  
5 study were well modelled assuming a mixture of (isolated/single) infinite planar (lamellar)  
6 sheets with the addition of one-dimensional paracrystals (stacks) to account for the presence  
7 in the sample of any multilamellar vesicles. The fits to the SANS data were obtained by the  
8 least-squares refinement of seven parameters, namely, the mean bilayer thickness ( $L$ ), the  
9 Lorentz factor ( $R_\sigma$ ), the number of bilayers in the stack ( $M$ ), their mean separation or d-  
10 spacing ( $D$ ), the width of the Gaussian distribution in the plane ( $\sigma(D)/D$ ), and the absolute  
11 scale factors for the unilamellar and multilamellar vesicles. During the analysis of the SANS  
12 data in the present study, the following factors namely,  $\sigma(L)/L$ ,  $\sigma(D)/D$  and  $R_\sigma$ , were fixed at  
13 0.1, 0.05 and 200, respectively. The only exception was the L-AuNP prepared using MF  
14 methodology where the value of  $R_\sigma$  had to be increased to 560 to fit satisfactorily fit the data,  
15 a lower value  $R_\sigma$  would not produce a reasonable fit of the data. In addition, when modelling  
16 the SANS data using a mixed population of sheets and stacks,  $L$ ,  $\sigma(L)/L$ , and  $R_\sigma$  were  
17 constrained to be the same for the isolated/single and stacked lamellae, a not unreasonable  
18 assumption. All the SANS data were fitted using a multilayer stack comprising of 3-4  
19 bilayers. For all models, the least-squares refinements were performed using the model-  
20 fitting routines provided in the FISH software<sup>47</sup>.

### 21 **Atomic Force Microscopy**

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23 Atomic force microscopy (AFM) analysis was performed to study the effect of nanoparticles  
24 incorporation on the bilayer thickness. L-AuNP hybrid dispersion (20  $\mu\text{L}$ ) loaded with 2.5  
25 mg/mL of Au nanoparticles and formulated via REV or MF methods were deposited on the  
26 surface of a sheet of freshly cleaved mica and were allowed to adsorb for 1 min. Non-  
27 adsorbed liposomes were washed off by filtered distilled water. Samples were then dried  
28 with dust-free argon gas. A Molecular Force Probe 3D AFM (MFP-3D, Asylum Research,  
29 Oxford Instruments, Abingdon, UK) equipped with a ScanAsyst-Fluid cantilever (Bruker,  
30 Camarillo, CA, USA) was used to acquire the AFM images in air at room temperature in  
31 tapping mode. The silicon nitride cantilever had a nominal spring constant of 0.7 N/m and a  
32 typical resonance frequency of 150 kHz. Different areas of the samples ( $< 10 \mu\text{m}^2$ ) were  
33 imaged at a scan rate and a resolution of 1 Hz and 512 x 512 pixels, respectively. Images  
34 were analysed with MFP-3D software (Oxford Instrument) and profiles were plotted with  
35 Origin 8.5 software.

## Results and Discussion

### Fabrication and Physicochemical Characterization of L-AuNP Hybrids

Microfluidics represent a promising technology for the scalable production of both nanoparticles and liposomes offering the possibility of a precise control over their size and polydispersity as well as the potential to increase drug loading capacity<sup>29, 36, 48, 49</sup>. When the organic and buffered aqueous phases are mixed in a microfluidics system, the polarity of the solvent increases gradually when compared to the polarity of the organic solvent in which the phospholipids were dissolved. As a consequence, the solubility of the phospholipids progressively reduces promoting their self-assembly into planar bilayer disc-like structures. These planar structures eventually close-up into spherical vesicles or liposomes<sup>36, 50</sup>. In the present study, L-AuNP hybrids were fabricated through self-assembly using either MF (Figure 1A) or REV methodology's (Figure 1B). Specifically the incorporation of three different concentrations of AuNPs, namely 2.5, 0.25 and 0.025 mg/mL, into self-assembled liposomes comprising of HSPC:DSPE-PEG<sub>2000</sub> (95:5) mol/mol has been investigated. To obtain the best level of incorporation of AuNP into the lipid bilayer, hydrophobically-derivatized AuNP of 2-4 nm size were used<sup>13, 22</sup>. The conditions for the microfluidic preparation of the L-AuNP were optimised using an automated Asia 320 microfluidic system (Syrris, Royston UK) equipped with an Asia 26  $\mu$ mixer reaction chip. PBS was selected as solvent for the aqueous phase because previous work had found that liposomes composed of DSPC lipids have smaller size when prepared in PBS buffer compared to other buffers such as Tris buffer<sup>36</sup>. The choice of the organic solvent plays a crucial role in the defining properties of the resultant liposomes including their size and stability. For example, the use of methanol, as is the case here, and isopropyl alcohol as solvent produces superior liposomes compared to when ethanol was used as solvent. This is the result of the tendency of ethanol to promote vesicle fusion and consequently liposome aggregation if it is not completely removed<sup>51</sup>. Methanol was selected as organic solvent for two reasons, namely it dissolves both HSPC and DSPE-PEG<sub>2000</sub> and because it is miscible with the PBS buffer. However, because the hydrophobic AuNPs, supplied suspended in toluene, have a tendency to aggregate in methanol, extra steps had to be incorporated into the MF preparation process in order to ensure that NPs were fully suspended. Consequently, after the evaporation of the toluene dispersing solvent, the AuNPs were re-suspended in CHCl<sub>3</sub> and mixed with the methanolic lipid solution and sonicated for 20 seconds in order to obtain a homogenous NPs dispersion. CHCl<sub>3</sub> was then removed from the sonicated mixture by 15-20 min evaporation at 460 mbar and at 40°C before the final AuNP lipid mixture was introduced into the microfluidics system. TEM images of the AuNP before and after evaporation of toluene and after resuspension in CHCl<sub>3</sub> confirmed the absence of AuNP aggregates (Figure S1 A&B). HSPC was specifically selected as the major lipidic component of the liposomes because earlier studies had demonstrated that lipids with long hydrophobic chains exhibited a higher capacity for the incorporation of hydrophobic molecules<sup>52, 53</sup>. In the same vein, cholesterol was not added to the formulation as it had been shown to reduce metallic NP incorporation into lipid bilayers<sup>54, 55</sup>. However, cholesterol is well known to have a significant effect on the structural stability and drug retention inside the liposomes under physiological condition. Thus, the effect of cholesterol on metallic NPs loading into the liposomes should be considered.

In agreement with earlier studies, we observed that the FRR, which represents the organic:water ratio at the mixing point, affects the size of the liposomes produced. In the present study, two FRRs, namely 1:5 and 1:10, were investigated. When the FRR is increased from 1:5 to 1:10, the increased volume of the aqueous solvent imposes a dilution on the organic solvent facilitating a rapid mixing<sup>56</sup> and thereby favouring the formation of small liposomes<sup>37, 49, 54</sup>. On the other hand, when a FRR of 1:5 was used, irrespective of the TFR and the running temperature, the resultant particles exhibited a bimodal distribution with a Z-average size of greater than 800 nm (data not shown). In contrast, when an FRR equal to 1:10 was used, liposomes characterised by small sizes and low PDI values were

observed when a TFR of less than 680  $\mu\text{L}/\text{min}$  and a running temperature of equal to or greater than  $60^\circ\text{C}$  were used (Figure S1C). This result was contrary to that of other researchers<sup>56, 57</sup> who have reported that the TFR used has little effect on the final size of the liposomes produced.

Additionally, the size of the liposomes was decreased by an increase in the experimental temperature up to  $65^\circ\text{C}$  (i.e. the temperature at which the micromixer chip was maintained during the mixing of the two phases) to above the  $T_m$  of the lipids ( $\sim 50^\circ\text{C}$ ) as determined by our anisotropy measurements and from previous literature.<sup>58, 59</sup> This effect of temperature is a consequence of the higher mobility of the phospholipid tails which results in the efficient, rapid mixing of the solvents in the chip, especially at the lower FRR. In this context it is worth mentioning that for a TFR  $\geq 1370\mu\text{L}/\text{min}$ , the residence time of the solvents in the micromixer channels prior to mixing is insufficient to ensure temperature equilibration. Therefore, at TFR values above  $1370\mu\text{L}/\text{min}$  (values between 680 and  $1370\mu\text{L}/\text{min}$  were not tested) mixing was not favoured mainly because the actual experimental temperature was less than  $T_m$ . This observation could explain why increasing the TFR above  $680\mu\text{L}/\text{min}$  resulted in the production of liposomes of an increased size. A better control of the size at higher TFR could be possible by simply change the geometry of the mixing chip.

Based on the observations made in the present study, the L-AuNP hybrids were routinely prepared using a FRR of 1:10, a TFR of  $220\mu\text{L}/\text{min}$  and a running temperature of  $65^\circ\text{C}$ .

In order to evaluate the benefits and drawbacks of using microfluidic technology for the production of L-AuNP hybrids, L-AuNP hybrids of comparable composition to those prepared using MF were prepared using REV methodology (Figure 1B),<sup>43, 60</sup> a method widely used for preparation of L-AuNP hybrids. Significantly, no (liposomal) size reduction step was required when using MF methodology, which is an advantage over the REV method which requires a reduction in liposomal size, here performed by 30 min of bath sonication at  $60^\circ\text{C}$ . Characterization of the L-AuNP hybrids using dynamic light scattering (Figures 2A-C) showed that the MF methodology produced L-AuNP hybrids with a more homogenous size distribution (i.e. a narrower PDI) compared to those prepared using the REV method (Figure 2D). These size data were confirmed by C-FFF, which showed that the REV method resulted in the production of a larger proportion of smaller size liposomes when compared to the single homogenous peak of approximately 100 nm recorded for the liposomes prepared using the MF method (Figure 2E).

The ability to finely tune all these parameters in the microfluidics set-up enables controlled mixing of the liquid interfaces to achieve the desired properties (e.g. size and PDI) of the final liposomes product. This can be achieved in a single process without the need for post-processing or changing the lipid composition of the liposomes<sup>30, 35</sup>. Cancer therapy is one example where size reduction of liposomes is desirable<sup>34</sup>. A recent study by Dong et al demonstrated that by using MF methodology it was possible to reduce the size of doxorubicin-loaded liposomes to 50 nm. As a result of that, improvement in tumour extravasation and intra-tumoral distribution was observed<sup>34</sup>.

#### **Quantification of L-AuNP Hybrids Loading by UV-Vis and ICP-MS**

Another advantage of the microfluidic production of liposomes is the enhanced capacity for their payload of therapeutic molecules. Interestingly, the payload capacity of hydrophilic drugs is almost doubled with MF technology compared to less than 10% obtained by traditional liposomes preparation methods.<sup>1</sup> Moreover, MF technology is highly efficient for incorporation of poorly water soluble drugs into the liposomes and has demonstrated the potential for entrapping both hydrophilic and lipophilic drugs simultaneously. Efficient loading of wide range of therapeutics has been reported. These include hydrophilic molecules (e.g.

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3 metformin, sulforhodamine)<sup>36, 61</sup> and hydrophobic molecules (e.g. glipizide and propofol)<sup>36,58</sup>  
4 either individually or in combination<sup>36</sup>. The aim of the present study was to explore the use of  
5 microfluidics for the fabrication of L-AuNP hybrids due to the poor payload capacity reported  
6 with other traditional methods.<sup>62</sup> The quantification of AuNPs embedded in the liposomes  
7 was performed using UV-VIS spectrometry (Figure 3A & Figure S2) and ICP-MS (Figure  
8 3B). Regardless of which of the assay methods was used, an increase in AuNP loading into  
9 the liposomes with increasing the initial AuNP concentration was observed. Significantly, a  
10 3-fold increase in loading efficiency was observed in the hybrid systems prepared by MF  
11 methodology when compared to the REV method at the highest initial concentration of AuNP  
12 examined, i.e. 2.5 mg of AuNPs. In comparison, no difference in the AuNP loading capacity  
13 between the two methods was observed at the lower initial AuNP concentrations of 0.025  
14 and 0.25 mg, although qualitative differences (discussed in the next paragraph) were  
15 observed in TEM images (Figures 4 A and B).  
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17 Size exclusion chromatography (SEC) was used to separate AuNPs that were not  
18 incorporated into liposomes. Quantification of the amount of phospholipid and Au, and  
19 therefore by implication the amount of AuNPs, in each fraction eluted indicated that the  
20 AuNP elution mirrors that of the liposomes (as assessed by phospholipid concentration) with  
21 very small amounts of AuNPs being detected in the other fractions, suggesting that the  
22 majority of AuNPs were incorporated into the liposomes, i.e. there were very minimum free  
23 AuNPs (Figure S3 & S4). This was also confirmed with TEM imaging of L-AuNP before and  
24 after elution through sepharose CL-4B column which confirmed that no free AuNP  
25 aggregates exist before purification and suggested that most of the AuNPs already  
26 incorporated into the liposomes (Figure S4 C&D). This was consistent for all the L-AuNP  
27 samples prepared by MF and REV methodology. Correction of any loss of lipid vesicles on  
28 the SEC was performed by measuring the lipid concentration with Stewart's assay. In  
29 addition, the separation of empty (i.e. AuNPs 'free') liposomes from L-AuNP hybrids was  
30 explored by centrifugation during which the L-AuNP hybrids were sedimented due to the  
31 dense AuNPs they contained, while the empty liposomes remained suspended in the  
32 supernatant. Qualitative validation of these data was obtained using TEM imaging (Figure  
33 S5) which showed clearly the separation of the L-AuNP-containing liposomes from the  
34 empty liposomes. Dynamic light scattering measurements of the two fractions indicated,  
35 irrespective of the method of preparation, an increase in the apparent hydrodynamic size of  
36 the liposomes in the presence of AuNP with sizes in the range 130-260 nm being recorded  
37 for the L-AuNP hybrids compared to sizes of less than 100 nm for the empty liposomes  
38 (Table S1).  
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41 The hybrids were also analysed by C-FFF, a technique which exploited both DLS and UV as  
42 detection methods which allowed the measurement of the apparent hydrodynamic size of  
43 particles and monitoring of the presence of any Au, respectively (Figure S5 C). When  
44 comparing the total particle population, the measured UV signal of the various liposomal  
45 preparations was found to be almost one order of magnitude higher for L-AuNP hybrids  
46 using MF methodology indicating higher AuNPs loading. Furthermore, the apparent  
47 difference in density ( $\rho - \rho_0$ ) between the sample and solvent determined for the various  
48 liposomal preparations studied was particularly pronounced for the L-AuNP hybrids prepared  
49 using the highest initial concentration of Au of 2.5 mg/mL, with those prepared using MF  
50 exhibiting the highest density difference and therefore by implication the highest  
51 concentration of AuNPs. The fraction of loaded and unloaded liposomes expressed as wt %  
52 of the total liposomes prepared by MF and REV was also calculated (Figure S5D). Data  
53 indicated that the fraction of Loaded liposomes is higher for MF compared to REV for all  
54 AuNPs concentrations tested.  
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### Qualitative Evaluation of L-AuNP Hybrids with Electron Microscopy

The morphological characterization of the L-AuNP hybrids was undertaken using transmission electron microscopy (Figure 4 A&B). The resultant TEM images confirmed the incorporation of AuNPs into the liposomes. Furthermore, in agreement with UV-VIS and ICP-MS measurements, the TEM images revealed a higher AuNP loading capacity for the systems prepared by the MF method. Unfortunately, detection of AuNPs in the liposomes at the lowest initial concentration of Au was not possible. TEM images also revealed the presence of mixed population of both loaded and unloaded liposomes. The association of AuNPs with the liposomes was confirmed with STEM EDS microscopy (Figures 4C & D) which verified the association of Au with the liposomes by elemental analysis. A tendency towards the formation of nanoparticles rich domains was noticed in the MF L-AuNP hybrids samples compared to mainly individualised nanoparticles present in the lipid bilayer of the REV L-AuNP hybrids.

To further probe the association of Au nanoparticles with the liposomes, the L-AuNP hybrids were studied using cryo-TEM. CryoEM illustrates qualitative distinctions between the hybrid systems produced by the two methods when incorporating the highest initial amount of AuNPs. Specifically, the MF methodology provided hybrids that contained a core of AuNPs aggregates (Figure 4E). In these systems the core looks to be “wrapped” by a number of lipid bilayers which create a multilamellar structure around it. The cryo-TEM images of the MF prepared L-AuNP hybrids indicated the co-existence of membrane-embedded and interdigitated (i.e. encapsulated nanoparticles with some association of the internal lipid membrane) AuNP-rich domains suggesting the structural stabilization of the AuNPs hydrophobic interactions. These findings are in agreement with a recent work from Cullis group that reported the use of microfluidics to encapsulate negatively charges AuNP inside positively charged L-NP. However, in their case structural stabilisation of the final system is through electrostatic interactions<sup>31</sup>. In contrast, the REV method was seen to result in the production of hybrids that predominately consist of two lipid bilayers and contain individual AuNPs or small aggregates of AuNPs (Figure 4F). Both unilamellar and multilamellar liposomes were present in the hybrids regardless of their preparation methods. Further CET studies performed on the L-AuNP hybrids prepared by MF confirmed the incorporation of AuNPs in the liposomes (Figure 5 & Supplementary Video). The ability to form multilamellar shell is very interesting and could have other possible applications such as increasing the loading efficiency of hydrophobic drugs. However, the factors responsible for controlling the number of layers in those multilamellar system and the effects of that on the physical properties of the final system need to be investigated. Nevertheless, since the % of nanoparticles incorporation into the lipid bilayer using the REV method is lower than MF, the overall effect of this incorporation on the lipid membrane fluidity is relatively minor.

### Effects of Au-NP Incorporation on Bilayer Thickness and Rigidity

The effect of the presence of the AuNPs on the properties of the hybrid systems was established using a combination of advanced biophysical tools, namely fluorescence anisotropy, SANS and AFM. Anisotropy is widely used to study the effect of nanoparticles incorporation on lipid membrane packing and fluidity because of its high sensitivity to size, position, concentration of nanoparticles incorporated and sensitivity to experimental temperature conditions<sup>63, 64, 65</sup>. As a reflection of this enhancement in AuNPs incorporation, an increase in ANS fluorescence anisotropy values were observed indicating a reduction in the membrane fluidity or a rigidifying effect close to the head group region of the lipid membrane (Figures 6A & C). This effect was observed throughout the temperatures tested (i.e. below and above the T<sub>m</sub> of the lipid membrane), particularly in the case of the hybrids prepared using MF methodology where there was a noticeable increased in anisotropy with initial AuNP concentration, suggesting that the bilayer rigidity close to the head group region was increased by increasing the concentration AuNP. In the hybrid systems prepared using the REV method, the anisotropy values were reduced and only in the case of the highest

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3 initial AuNP concentration was an increase observed. Previous studies have demonstrated  
4 the ability of ANS molecules to penetrate the lipid bilayer and interact with the head group  
5 region on the inner and outer surface of the lipid bilayer<sup>66, 67</sup>. Therefore, we expect that ANS  
6 anisotropy data to reflect the effect observed from both unilamellar and multilamellar vesicles  
7 in both methods. The effect of L-AuNPs hybrids size on membrane curvature and lipid  
8 packing might also affect ANS anisotropy data and should be taken in consideration when  
9 interpreting the results.

10 On the contrary, minute changes were detected from DPH anisotropy demonstrating  
11 minimum nanoparticle association with the core of the lipid membrane (Figures 6B & D). No  
12 significant effect of changing the initial AuNP concentration was detected on the  $T_m$  of the  
13 liposomes when prepared using either methodology ( $T_m \sim 50^\circ\text{C}$  for MF hybrids vs  $\sim 46^\circ\text{C}$   
14 for REV hybrids). The lower  $T_m$  recorded from REV hybrids could be due to the presence of  
15 residual solvents that interdigitate in the lipid bilayer and results in distortion of lipid packing  
16 and hence reduced  $T_m$  compared to MF hybrids. The findings in the current study agree with  
17 previous studies reporting that the incorporation of small hydrophobic nanoparticles (< 5nm)  
18 increases membrane rigidity. On the contrary, nanoparticles bigger than 5 nm result in the  
19 distortion of the membrane effect causing an increase in lipid membrane fluidity<sup>23, 68</sup>.  
20 In agreement with the anisotropy findings, SANS data (Figures 6E & F and Figure S6, Table  
21 3) indicated that the incorporation of AuNPs into the liposomes resulted in a slightly thicker  
22 ( $L = 49.1 \pm 0.2$  vs.  $45.6 \pm 0.1$ ), more rigid bilayer ( $R_g = 560$  vs 200) in the hybrid systems  
23 fabricated by the MF method and containing the highest initial load of AuNPs when  
24 compared to the corresponding hybrids prepared by the REV method and the 'empty'  
25 liposomes. This observation may be a consequence of the differences in the loading  
26 efficiency between the two methods. SANS also indicated the co-existence of both  
27 unilamellar and multilamellar vesicles for both methods with the amount of multilamellar  
28 vesicles present being lower in the vesicles prepared using the MF methodology (Table 3) -  
29 a result that correlates well with the cryo-TEM findings.

30 Surface topography of L-AuNP hybrids was examined by AFM. Profile analysis performed  
31 using the AFM images (Figure 7) indicated that AuNP incorporation increased the height (i.e.  
32 thickness) of the lipid bilayer from 4-5 nm ('empty' liposomes) to almost 8-10 nm (L-AuNP  
33 hybrids) for both preparation methods tested at the highest initial AuNPs concentration. This  
34 result was in agreement with studies previously published by ourselves and others who  
35 reported an increase in the bilayer thickness after nanoparticle incorporation<sup>43, 69</sup>.  
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**Table 3:** Structural parameters obtained through fits to the SANS data obtained for vesicle dispersions prepared from the various liposomal preparations at  $25 \pm 0.1^\circ \text{C}$ . Symbols used are as described in the text

Liposomal preparations	Mean bilayer thickness (L) Å	The Lorentz factor ( $R\sigma$ ) Å	Mean separation or d-spacing (D) Å	Number of bilayers in the stack (M)	Ratio of Unilamellar: Multilamellar surface area
Empty liposomes	45.6(0.1)	200	$64.9 \pm 0.2$	3	1.5
MF L-AuNP 2.5	49.1(0.2)	560	$72.5 \pm 0.3$	4	2.7
REV L-AuNP 2.5	45.6(0.1)	200	$64.9 \pm 0.2$	3	1.4

For L, the figures in parentheses show standard errors; for D, the uncertainties reported represent the convolution of the statistical error on D and the value of the fitted polydispersity.

Overall, our structural characterization corroborated the two proposed models of AuNP association with the liposomes, namely the membrane embedded and the encapsulated models. In agreement with TEM images, a mixed population of AuNP loaded and unloaded liposomes were detected. In the case of the MF L-AuNP hybrids, the co-existence of lipid bilayer embedded AuNPs (i.e. the membrane embedded model) and AuNPs inside the liposomes (i.e. the encapsulated model) with some interaction with internal lipid membrane was observed. In contrast, membrane embedded AuNPs were found to exist in the majority of REV L-AuNP hybrids with a minority of encapsulated AuNPs being observed. SANS and AFM observations reinforced anisotropy measurements that confirm the increase in the bilayer thickness for MF L-AuNP hybrids systems.

Optimization processes reported here are all based on one specific instrument (Asia 320 microfluidic system). Whether the process can translate and expand to other types of microfluidic systems requires further investigation.

Collectively, our results demonstrate that by using a microfluidic method of preparation we were able to improve the loading of hydrophobic metallic NPs into liposomes when compared to the traditional REV method. The results obtained in this study using a commercial microfluidics system enables the reproducible, automated manufacture of L-AuNP hybrids. Other critical factors that may be worth exploring in the future are the effect this enhanced loading could have on the encapsulation efficiency of imaging and/or theranostic systems. More work needs to be undertaken to prove that the enhanced payload of AuNP observed in the L-AuNP hybrids can be translated into a higher efficiency for such systems. Moreover, the concentration AuNP loaded inside the liposomes should be carefully selected to ensure that theranostic properties of AuNP is not lost due to possible aggregation if very high concentration is loaded.



## Conclusions

We have demonstrated for the first time the fabrication of L-AuNP hybrids using automated microfluidic technology. The L-AuNP hybrids prepared in the present study showed a more homogenous size distribution and correspondingly smaller PDI compared to those made using the traditional REV methodology. Most significantly, the capacity of the nanoparticles prepared using microfluidic technology for its AuNPs payload was three times that of the REVs prepared using traditional methodology. Detailed structural characterisation of the L-AuNP hybrids using a range of advance biophysical methods confirmed the superiority of the microfluidics for the preparation of nanoparticle-containing liposomes. The data also revealed the co-existence of membrane embedded and interdigitated nanoparticles-rich domains which are understood to be a consequence of both the size of the AuNPs studied and their hydrophobic nature. The present findings demonstrate the benefit that microfluidic technology offers in the preparation of hybrid nanoparticles with improved fabrication and functionality and to expedite their translation for imaging and/or therapeutic purposes.

## Supporting Information

Supporting Information are available free of charge that covers the following areas; TEM images of Au NPs under different conditions, standard curves for lipids and Au NPs measurements, UV-Vis spectra for Au NPs, purification process of L-AuNP hybrids using a sepharose CL-4B column, separation of L-AuNP hybrids from unloaded liposomes by centrifugation, small angle neutron scattering data (dots) for plain 'empty' liposomes and colloidal properties of L-AuNP hybrids.

## Conflict of interest

The authors declare that there is no conflict of interest.

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## Author Contributions

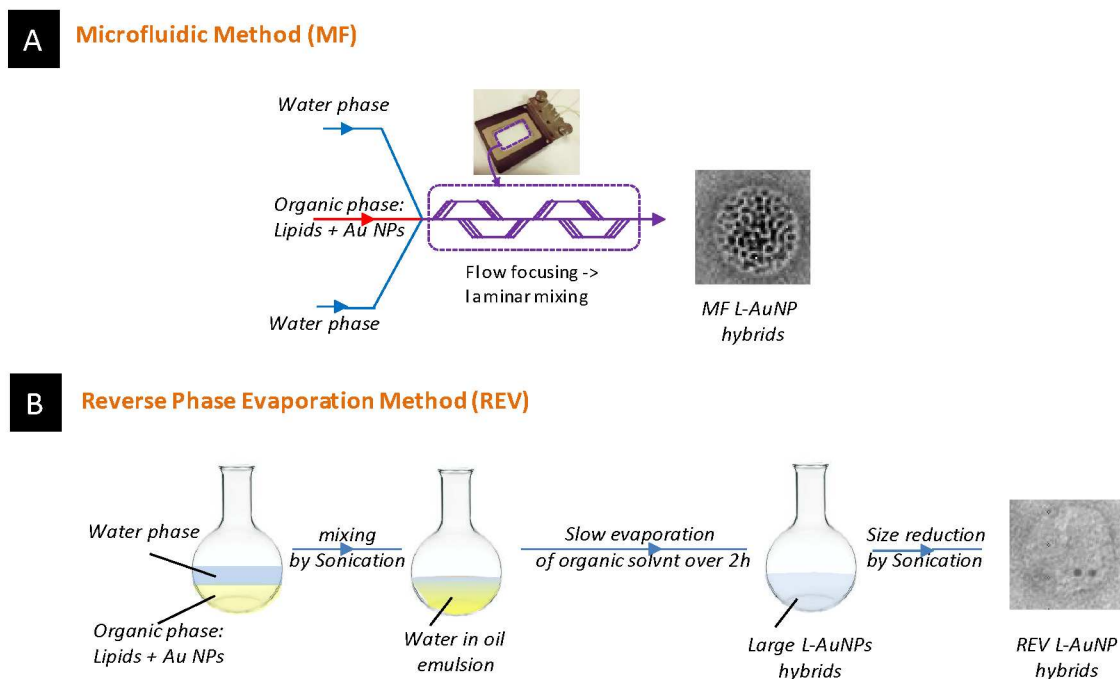
Z.A. designed, planned, and led the study, preparing the L-AuNP hybrids and performing most of the biophysical characterization including quantification of the Au nanoparticles using UV and ICP-MS measurements, anisotropy studies, purification, and separation studies, prepared figures and wrote the manuscript. R.D. ran the microfluidics system and prepared MF L-AuNP hybrids, optimised the parameters for microfluidic experiments, performed the AFM data acquisition, analysed and coordinated the cryo-TEM and CET imaging and prepared figures 5 and 7. A.G performed and analyzed the C-FFF studies. E.P. acquired and analyzed STEM images. R.M. performed and analysed the cryo-TEM images. A.M. acquired the TEM images. L.N. prepared samples for STEM imaging and provided advice on ICP-MS studies. M.J.L. performed and analysed SANS studies. N.T. & K.K. discussed the findings and reviewed the manuscript. Z.A., R.D., M.A., M.J.L, N.T., K.K. discussed the findings, reviewed and edited the manuscript.

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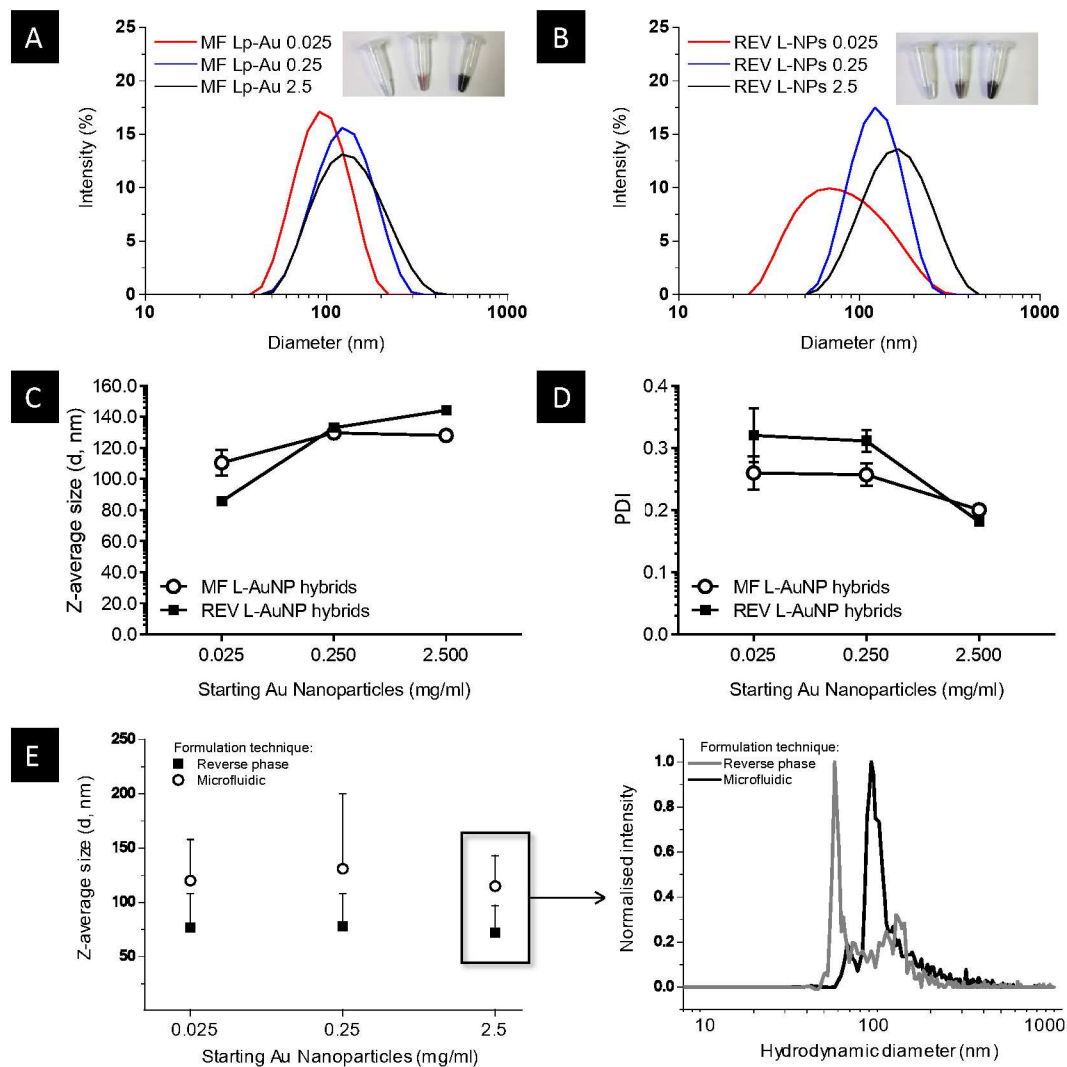
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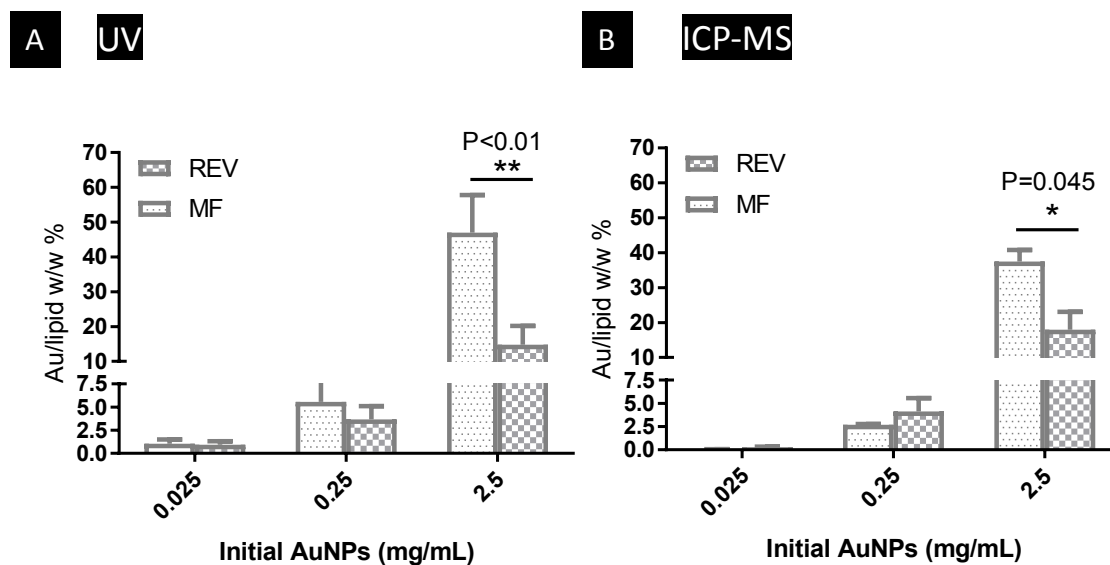
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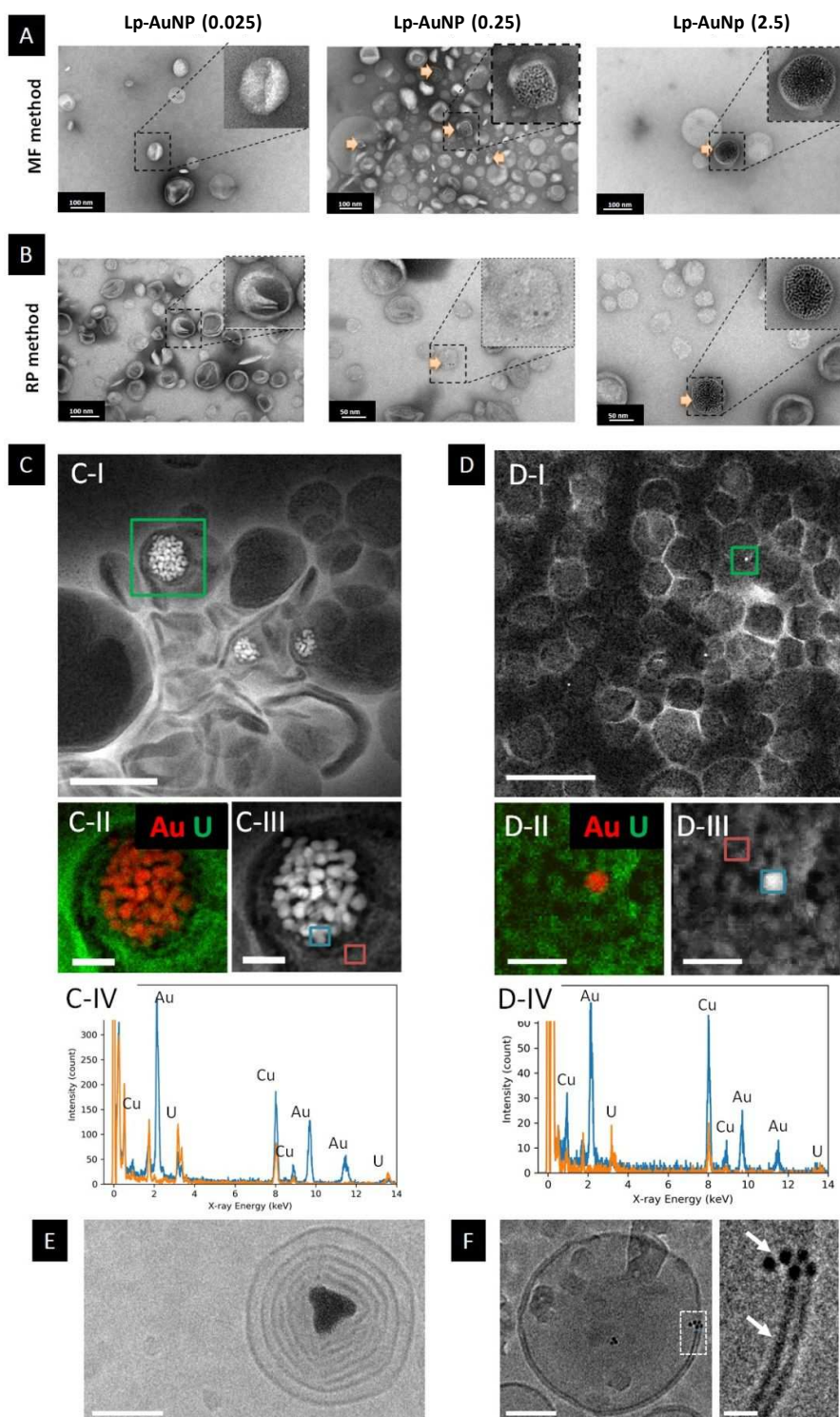
**Figure 1:** Schematic representation of L-AuNP hybrid production by A) microfluidics methodology (MF) and B) reverse phase evaporation (REV) methodology showing the different steps involved in each method. No size reduction step is needed for L-AuNP hybrid production via the MF method while liposome size is reduced by sonication for production with the REV method.



**Figure 2:** L-AuNP hybrid characterisation via photographic images and intensity distribution measurements as determined by dynamic light scattering prepared by A) the microfluidic (MF) and B) the reverse phase evaporation (REV) methods using different initial amounts of AuNP, namely 0.025, 0.25 and 2.5 mg/mL; C) the mean Z average apparent hydrodynamic diameter and D) polydispersity index of the corresponding L-AuNP respectively; E) the mean Z average apparent hydrodynamic diameter of L-AuNP hybrids after separation by centrifugal field flow fractionation (C-FFF) and the corresponding intensity distribution of the L-AuNP prepared using the highest initial concentration of AuNPs. Error bars refer to the width of the distribution. Samples are measured at 25 °C, n = 3.



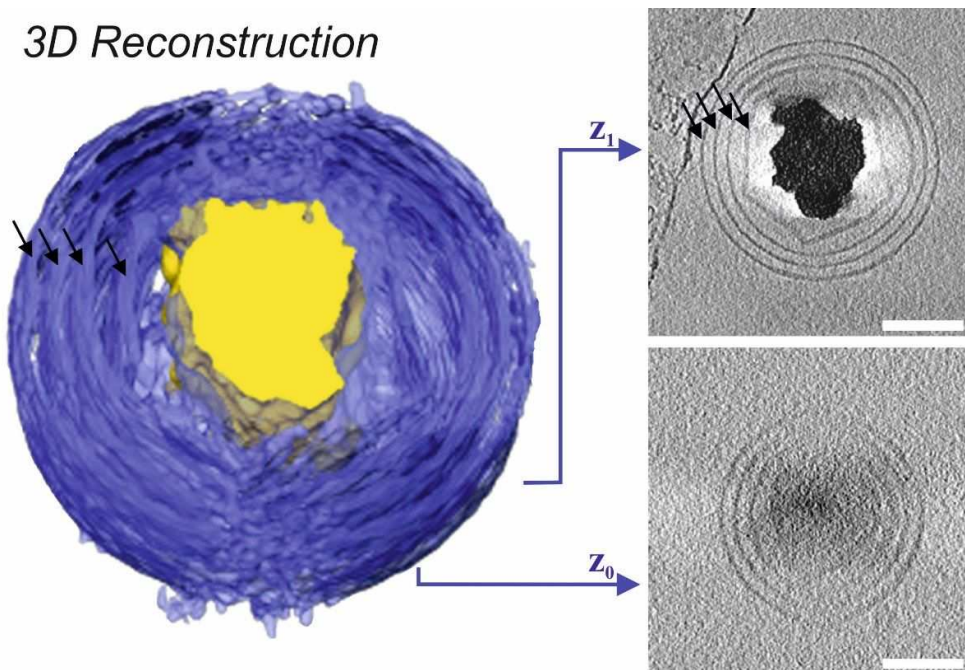
**Figure 3:** Quantification of the loading capacity of L-AuNP hybrids by the microfluidic (MF) and the reverse phase evaporation (REV) methods with different initial amounts of AuNP, namely 0.025, 0.25 and 2.5 mg/mL as determined by A) UV-VIS spectrophotometry and B) inductively coupled plasma mass spectrometry (ICP-MS). Data are expressed as a wt% gold (Au) per wt lipid. Quantification of lipid concentration in each sample was performed by Stewart's assay. Samples measured at room temperature,  $n = 3$  for UV measurements and  $n=2$  for ICP-MS measurements.



**Figure 4:** Characterisation of L-AuNP hybrids by electron microscopy. TEM images of L-AuNP hybrids prepared by A) MF method and B) REV method with different initial amounts of AuNP, namely 0.025, 0.25 and 2.5 mg/mL. It was not possible using TEM to detect AuNPs in the liposomes with the lowest amount of AuNPs. HAADF image of L-AuNP hybrids 0.25 prepared by C) MF and D) REV methods highlighting inside the green box representative regions of liposomes containing aggregates of AuNPs (MF method) and a small number of individual nanoparticles (REV method). Au-L and U-L composite elemental (Au and U) map obtained by XEDS and simultaneously acquired

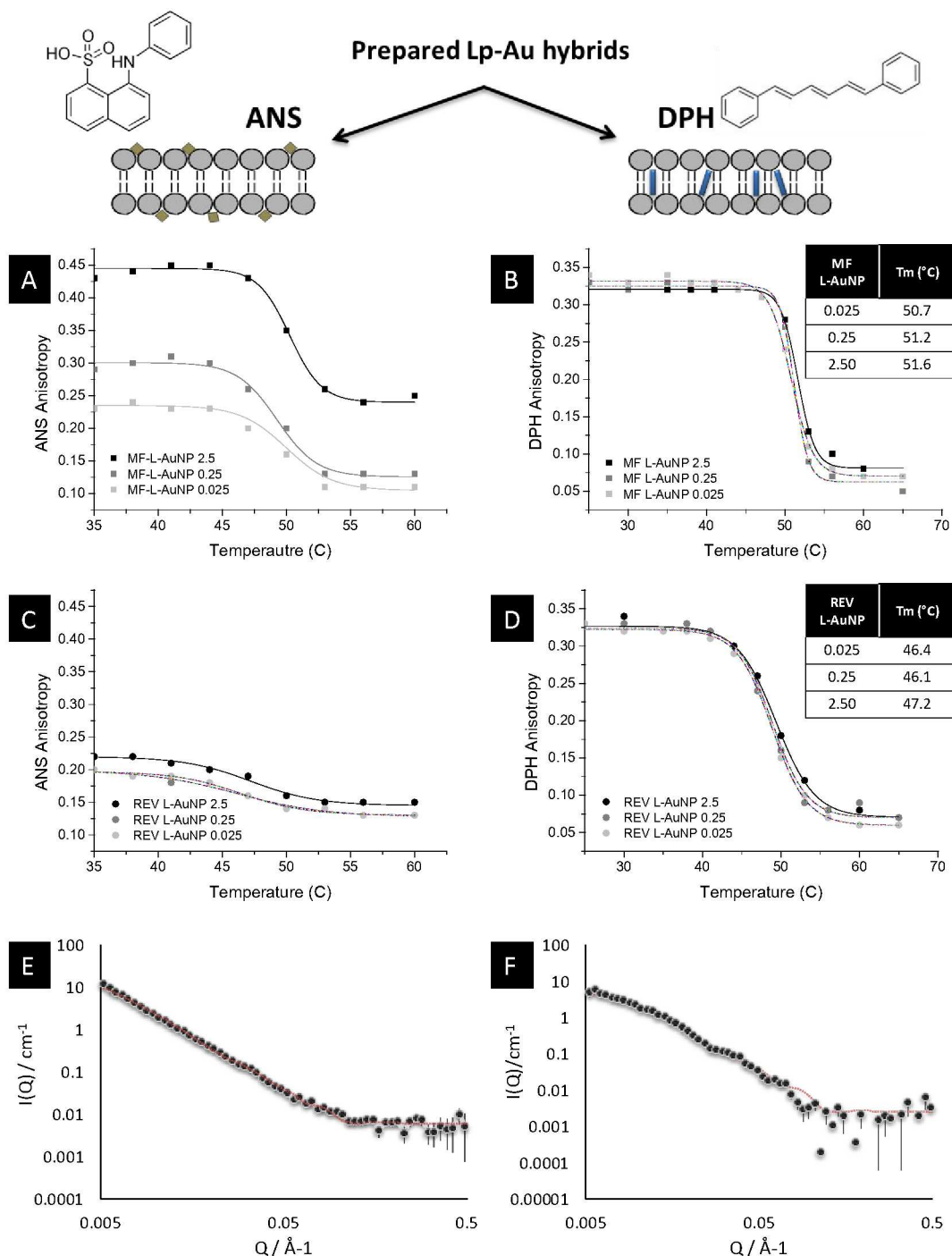


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3 HAADF images of the highlighted area of L-AuNP hybrids prepared by the MF method CII) and CIII)  
4 and the REV method DII) and DIII). XEDS spectra show Au from the AuNPs in blue and the area  
5 surrounding the AuNPs in orange. CryoEM images of L-AuNP hybrids prepared by E) the MF method  
6 and F) and the REV method with an initial amount of AuNP, namely 2.5 mg/mL. The scale bars for CII)  
7 (left) & 10 nm (right).

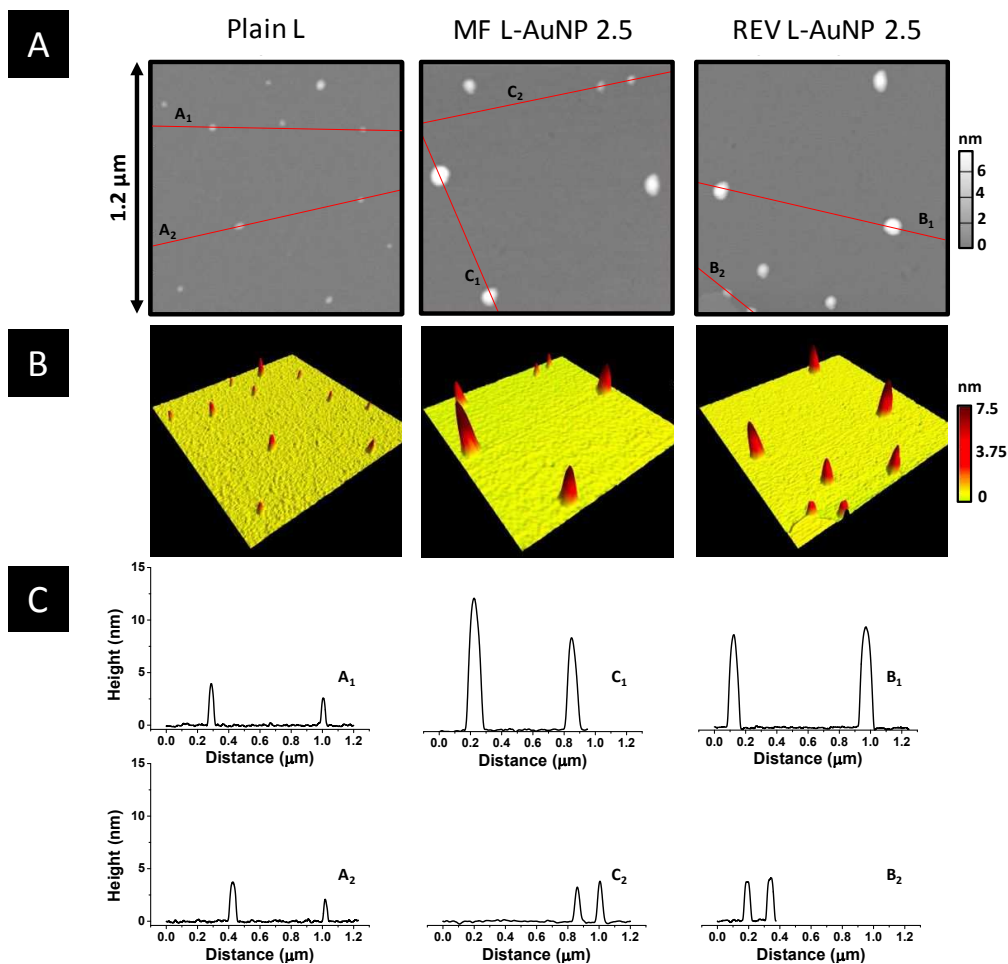


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**Figure 5:** 3D model obtained from the cryo-tomography performed on a multilamellar liposome produced by the MF method. On the right, two z-stack images are provided. It was possible to observe the multilamellar structure (black arrows point the different phospholipid layers) and to demonstrate that the Au-NP agglomerate is incorporated into the liposome. Scale bar = 100nm. Please, note that the 3D model has been segmented in order to remove unwanted artefact (see Supplementary Video).



**Figure 6:** Variation of fluorescence anisotropy of ANS A) & C) and DPH B) & D) in L-AuNP hybrids prepared by A) and B) microfluidic (MF) and C) and D) the reverse phase evaporation (REV) methods using different initial AuNP concentrations, namely 0.025, 0.25 and 2.5 mg/mL over the temperature range 25°C until 65°C. Fluorescent data of DPH anisotropy were fitted to obtain the phase transition temperature ( $T_m$ ) as indicated by the inset tables in B & D. Small angle neutron scattering data (dots) and the best fit to the data (solid line) obtained using the mixed sheet and stack model for L-AuNP hybrids prepared by E) MF and F) REV methodology measured at 25°C.



**Figure 7:** Characterisation of empty liposomes (plain L) and L-AuNP hybrids (MF L-AuNP 2.5 and REV L-AuNP 2.5) by atomic force microscopy showing A) amplitude, B) 3D images and C) cross-section analysis). Measurements performed at 25°C.

Graphical Abstract

