Liposomal formulation of amphiphilic fullerene antioxidants

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Abstract:

Novel amphiphilic fullerene[70] derivatives that are rationally designed to intercalate in lipid bilayers are reported, as well as its vesicular formulation with surprisingly high loading capacity up to 65% by weight. The amphiphilic C_{70} bisadduct forms uniform and dimensionally stable liposomes with auxiliary natural phospholipids as demonstrated by buoyant density test, particle size distribution, and ^{31}P NMR. The antioxidant property of fullerenes is retained in the bipolarly functionalized C_{70} derivative, amphiphilic liposomal malonylfullerene[70] (ALM), as well as in its liposomal formulations, as shown by both electron paramagnetic resonance (EPR) studies and in vitro reactive oxygen species (ROS) inhibition experiments. The liposomally formulated ALM efficiently quenched hydroxyl radicals and superoxide radicals. In addition, the fullerene liposome inhibited radical-induced lipid peroxidation and maintained the integrity of the lipid bilayer structure. This new class of liposomally formulated, amphipathic fullerene compounds represents a novel drug delivery system for fullerenes and provides a promising pathway to treat oxidative stress-related diseases.

Keywords: fullerenes | liposomes | novel fullerene delivery

Article:

Introduction

Fullerenes and their derivatives have been proposed as free radical scavengers (1), and a number of investigations have studied fullerene (C_{60}) derivatives as potential free radical antioxidant therapeutics (2-5). Fullerenes (both pristine and derivatized fullerenes) have a tendency toward aggregation in aqueous environments making them unsuitable for therapeutic applications. For example, formulation techniques for preparing fullerene-based therapeutic candidates include host−guest complexation with cyclodextrins and calixerenes, surfactant solubilization with

Tween-20 and polyvinylpyrrolidone (PVP), and so forth. These preparations have their respective limitations in terms of uniformity of formulation, loading capacity, aggregation, and partition coefficient (5). Derivatization of fullerenes by directly adding moieties to the carbon cage has been used as a strategy to produce useful drug candidates. Such fullerene compounds including polyhydroxylated C_{60} (fullerenol) (6, 7), polysulfonated C_{60} (8), and carboxylated fullerenes (9, 10) have been shown to block free radical damages in several oxidative stress-related diseases including ischemia/reperfusion injury, inflammatory apoptosis, and neurogenerative diseases. However, aggregation in aqueous media to form particles with a broad range of diameter distributions is a general problem for many of those compounds (11). Polyderivatized fullerenes are often a mixture of many compounds, poorly characterized and not suitable for pharmaceutical development. In addition, it has been shown that cytotoxicity of fullerenes is related to the degree of cage derivatization, water solubility, aggregation, and particle size (11). An alternative approach in which fullerenes are encapsulated in bilayer vesicles such as liposomes has been proposed to overcome these limitations. Bensasson described the preparation of vesicles by incorporating C_{60} into l-α-phophatidyl choline purified from egg yolk (Egg-PC) (12). However, the authors reported that only 3% or less C_{60} was incorporated in Egg-PC liposomes and the preparation was not uniformly reproducible. Incorporation of C_{60} into l-α-phophatidyl ethanolamine (PE) was limited to 7% (13). Fullerene liposomes have also been prepared by transferring fullerenes from their water-soluble host−guest complexes (C_{60}·γ-CD and C_{70}·γ-CD) to lipid membranes for photodynamic therapy (PDT) (14, 15). The limited number of reports on liposomal fullerene formulations were all intended to use underivatized fullerenes that are not lipophilic, rather aromatic, and structurally incompatible with natural phospholipids; therefore, the fullerene contents were low and their dimensional stabilities were problematic. Further, the loading capacity of lipophilic drugs physically entrapped in the liposome bilayer is limited because of the membrane destabilization effect. Thus, it is necessary to develop new drug delivery strategies that can efficiently deliver fullerenes for therapeutic applications.

Given the low contents of pristine fullerenes in liposomal formulations, we hypothesized that incorporating amphiphilic fullerenes in vesicles would greatly increase their ability to be intercalated within the lipid bilayers. Herein, we report the design and synthesis of this new class of amphiphilic fullerenes, their liposome formulation and biological activities as radical scavengers. A key to obtaining a uniform vesicular preparation with high fullerene content and dimensional stability is to incorporate amphiphilic fullerene derivatives which mimic the structure of natural phospholipids. Hirsch has reported amphiphilic C_{60} derivatives in which multiple aliphatic hydrocarbons were attached at various sites on the fullerene cage (16, 17). However, these “buckysomes” do not assemble into stable bilayers readily, and the addition of multiple groups could significantly damage their bioactivity.

Figure 1 illustrates the design strategy in which the amphiphilic fullerenes and phospholipids are hypothesized to coassemble and form bilayer vesicles. As shown below, this method leads to highly increased loading capacity of fullerenes. The amphiphilic fullerene compounds do not form bilayer vesicles by themselves, but require membrane-forming lipids with lipid-to-fullerene molar ratio greater than 1:1 in order to produce uniform and dimensionally stable vesicles. We have also discovered that the oval structure of C_{70} molecule (as opposed to the spherical C_{60}) provides a novel structural platform to prepare this new type of amphiphilic fullerenes. C_{70} has

two reactive poles and a relatively inert equatorial region, and this allows for sequentially attaching lipophilic and hydrophilic groups at the two poles, respectively (18). The large underivatized zone around the C_{70} belt has very high radical reactivity due to the significant orbital overlap of its lowest unoccupied molecular orbital (LUMO) and highest occupied molecular orbital (HOMO) that is expected for sites of maximum radical reactivity (19-21). The fullerene-enriched liposome provides a novel formulation approach that not only enhances the fullerene delivery efficiency, but also maintain their antioxidative properties.

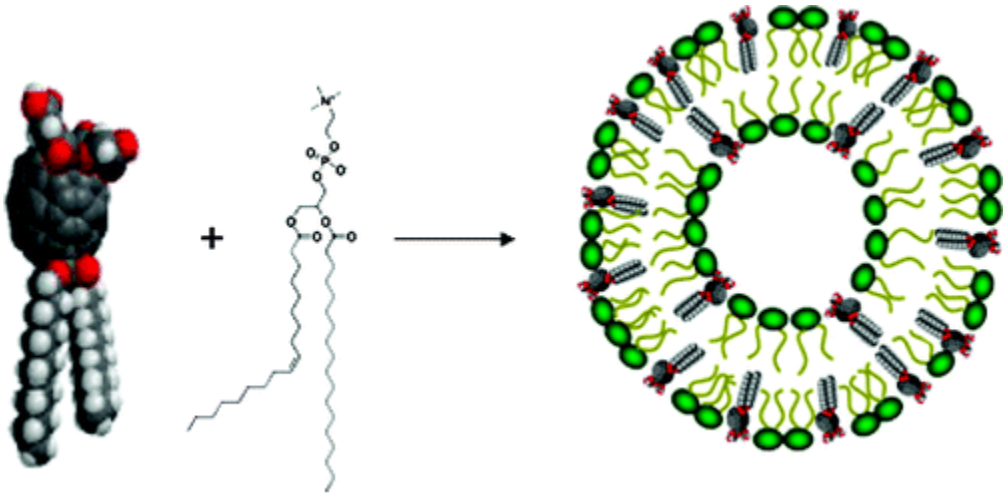


Figure 1. Vesicle formation of amphiphilic fullerenes with auxiliary phospholipids.

Materials and Methods

Synthesis of C_{70} Monoadduct 2. To a stirred solution of C_{70} (84.0 mg, 0.1 mmol), didodeceylmalonate **1** (44.0 mg, 0.1 mmol) prepared using literature procedure (22), and iodine (25.4 mg, 0.1 mmol) in 60 mL of dry toluene was added dropwise a solution of DBU (38.0 mg, 0.25 mmol) in 5 mL of dry toluene under nitrogen at room temperature. Upon completion of addition, the reaction mixture was stirred for an additional 3 h. The reaction mixture was then washed with brine and dried over anhydrous $MgSO_4$. The raw mixture was subjected to flash chromatography on silica gel. Unreacted C_{70} was removed by eluting the column with a mixture of toluene and hexanes (60/40, v/v), and then, the eluant was changed to toluene/hexanes (90/10, v/v) to give the product **2** (108 mg, 85%). The undesirable bisadducts were eluted from the column with DCM. MALDI-MS: 1278.4, ^{1}H NMR ($CDCl_3$): δ 0.79 (6H, t), 1.20 (32H, m), 1.38 (4H, m), 1.75 (4H, m), 4.37 (4H, t); ^{13}C NMR ($CDCl_3$) δ 14.5, 22.3, 25.8, 28.7, 29.1, 29.2, 29.3, 29.8 (3×), 31.9, 37.2, 67.0, 130.7, 130.8, 130.9, 132.8, 133.6, 137.0, 140.7, 141.6, 142.2, 142.8, 143.0, 143.5, 143.8, 143.9, 144.9, 145.9, 146.0, 146.5, 147.0, 147.3, 147.5, 147.6, 148.4, 148.5, 148.6, 148.8, 149.1, 149.3, 149.4, 150.6, 150.8, 151.2, 151.3, 151.4, 155.1, 163.5.

Synthesis of Di(*tert*-butylglycolate)malonate 3. To a stirred solution of malonic acid (1.04 g, 10 mmol) in 60 mL 1,4-dioxane was added 2.78 mL of TEA (2.02 g, 20 mmol). The mixture was stirred for 15 min before *tert*-butyl bromoacetate (4.68 g, 24 mmol) was added dropwise. The resulting mixture was vigorously stirred for 2−3 days until the reaction was complete as monitored by TLC. The precipitates were then filtered and the filtrate was washed twice with brine, dried over $MgSO_4$, and rotavaped in vacuo to give the pure di(*tert*-

butylglycolate)malonate **3** as a colorless oil (2.92 g, 88%). ^{1}H NMR ($CDCl_3$): δ ppm 1.39 (18H, s), 3.51 (2H, s), 4.49 (4H, s); ^{13}C NMR ($CDCl_3$) δ ppm 28.5, 40.2, 61.4, 82.3, 165.5, 167.3.

Synthesis of ALM. To a stirred solution of monoadduct **2** (127.8 mg, 0.1 mmol), di(*tert*-butylglycolate)malonate **3**(33.2 mg, 0.1 mmol), and iodine (25.4 mg, 0.1 mmol) in 60 mL of dry toluene was dropwise added a solution of DBU (35.0 mg, 0.22 mmol) in 5 mL of dry toluene under nitrogen at room temperature. The resulting reaction mixture was stirred for 6 h. The reaction mixture was washed with brine and then dried over anhydrous $MgSO_4$. The raw mixture was subjected to flash chromatography on silica gel. Unreacted monoadduct was removed by eluting the column with toluene, and then the eluant was changed to DCM to give the product (121 mg, 75%). MALDI-MS: 1608.2. ^{1}H NMR ($CDCl_3$): δ 0.75 (6H, m), 1.19 (32H, m), 1.38 (4H, m), 1.43 (18H, s), 1.71 (4H, m), 4.39 (4H, m), 4.75 (4H, m). The product diester (80.0 mg) was dissolved in a mixture of 30 mL DCM and 9 mL TFA, and stirred for 2 h. The solvent was evaporated and dried under vacuum to quantitatively yield pure ALM. MALDI-MS: 1498.2 (see MALDI-MS spectra in Supporting Information), ^{1}H NMR (DMSO): δ 0.79 (6H, m), 1.21 (32H, m), 1.39 (4H, m), 1.74 (4H, m), 4.40 (4H, m), 4.78 (4H, m).

Liposome Preparation. Two parts (by weight) of egg-PC or other lipids such as DMPC and DSPC were added to one part amphipathic ALM in diethyl ether (1 mg/mL). The addition of lipids enhanced the solubility of ALM, although ALM itself has reasonable solubility in diethyl ether. The mixture was sonicated for 2 min before filtration via 0.2 μm filter. To the filtrate, an aqueous buffered solution (PBS, phosphate buffered saline, pH = 7.4) was added, and the two-phase mixture was sonicated in a bath sonicator while purging with nitrogen to produce oligolamellar vesicles. Those oligolamellar vesicles were extruded with nucleopore membranes of 0.4, 0.2, and 0.1 μm, twice each pore size. The final ALM concentration in liposome suspensions was determined by UV−vis spectroscopy with a standard curve after extracting it to organic solvents. Size distribution of extruded liposomes was measured by dynamic light scattering (DLS) with Zetasizer nano S90.

Inhibition of Lipid Peroxidation. Dye-encapsulated liposomes were prepared by adding a buffered solution of the dye HPTS (20 mM, pH = 6.6) to an ether solution of egg-PC lipids (1 mg/mL) with or without ALM (1% by weight), purging nitrogen to remove ether in a bath ultrasonicator at room temperature, and extruding the crude liposomes with 400, 200, and 100 nm nuclear-pore membranes twice each. Dye-encapsulated liposome materials were separated from free dyes by SEC (size exclusion chromatography) on a Sephadex G-50 column with a buffered solution (pH = 7.8) (23, 24). The final dye concentration was 0.2 mM as determined by its UV−vis absorption. The absorption spectrum of the purified dye-encapsulated liposome samples were taken before and after the addition of Fenton reagents, and the final concentrations of H_2O_2 and $FeSO_4$ are 1 mM and 0.05 mM, respectively. Each scan was recorded at 30 min, 1 h, 2 h, 4 h, 8 h, 16 h, 24 h, 32 h, and 48 h after the radical initiation. The absorbance ratio ($A_{450\ nm}/A_{405\ nm}$) and absorbance difference ($A_{450\ nm} - A_{405\ nm}$) were plotted as a function of reaction time.

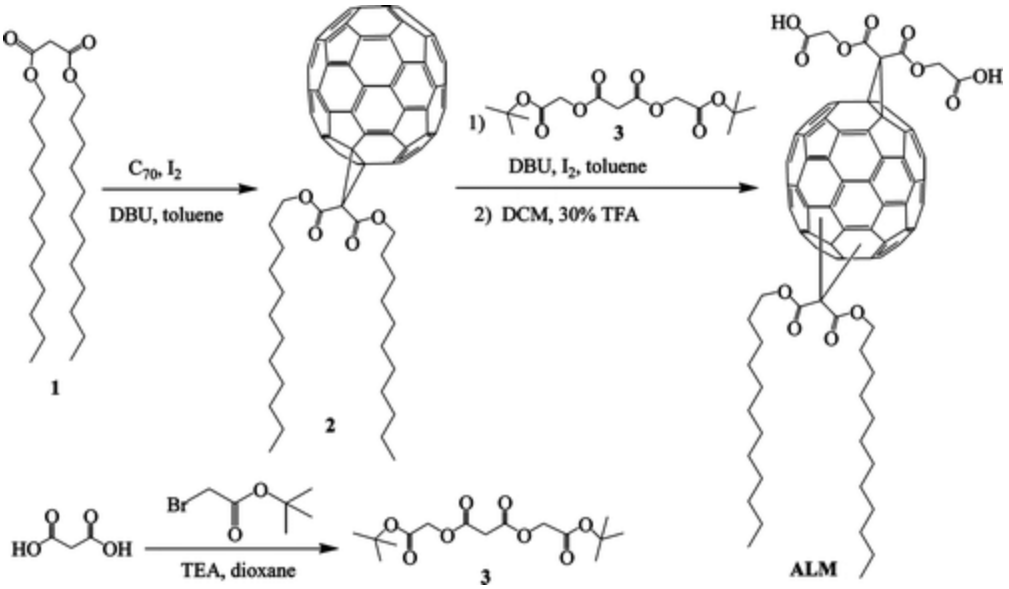
EPR Experiments. EPR studies on radical quenching (hydroxyl radicals and superoxide radicals) were performed as described (25). Compound ALM was dissolved in dry DMSO at 1.0 mg/mL (0.67 mM), and DMSO was run as a vesicle control. Hydroxyl radicals were generated

using standard concentrations of Fe^{2+}/H_2O_2 through Fenton reactions. Superoxide radical anions $O_2^{\cdot -}$ were generated through xanthine oxidase metabolism of hypoxanthine (HX/XO). EPR signals were acquired after 20 min incubation of ALM with radical-generating systems.

Cellular ROS Inhibition. U937 monocyte cells obtained from ATCC (Manassas, VA) were cultured in RPMI-1640 media supplemented with 10% FBS (fetal bovine serum). Cells were pretreated with ALM liposome or control liposome or untreated overnight in a 37 °C incubator with 6% CO_2, washed, and resuspended in RPMI medium containing 5 μM DCFH-DA (2′,7′-dichlorodihydrofluorescein diacetate) at 37 °C for 30 min. After incubation, the cells were washed (to remove any excess DCFH-DA) and activated with 10 μg/mL LPS (lipopolysaccharide). Activation-induced changes in mean fluorescence were measured in real time using a Perkin-Elmer LS55 Spectrofluorometer with excitation at 502 nm and emission at 523 nm for 15 min. The data are presented as fluorescence intensity of the 523 nm emission over time. All experiments were performed in triplicate. The ROS inhibition was defined as the percentage of the loss of DCF fluorescence when treated with liposome samples relative to the fluorescence intensity of untreated ones. Separate experiments were performed to ensure that the liposomal fullerenes do not interfere with the indicator dye in terms of the intensity of fluorescent signals.

Results and Discussion

Synthesis. Scheme 1 shows the synthesis of amphiphilic C_{70} compound ALM. The hydrophilic and hydrophobic groups are introduced to C_{70} through two-step cyclopropanation reactions of respective malonates under typical Bingel-Hirsch conditions in high yield (26, 27). Di(*tert*-butylglycolate)malonate **3** was prepared from malonic acid and *tert*-butylbromoacetate in the presence of TEA (triethylamine) in 1,4-dioxane at room temperature for 2−3 days. After solvents were evaporated, two-phase extraction (water and chloroform) yielded pure compound **3** in 85% yield. C_{70} monoadduct **2** was synthesized in 80% yield by reacting $C_{70}$and didodecylmalonate **1** and purified with silica gel column. Compound **2** then underwent the second cyclopropanation reaction with malonate **3** to produce the protected precursor of ALM, which was subsequently treated with 30% TFA (trifluoroacetic acid) in DCM to deprotect the *tert*-butyl esters and produce the amphiphilic compound ALM (22). Both ALM and its *tert*-butyl ester precursor were fully characterized by NMR, MALDI-MS, FT-IR, and UV−vis absorption spectroscopy. In addition, we have demonstrated that the three regioisomers of the C_{70} bisadduct ALM could be separated by reverse-phase HPLC (0.1% TFA in ethanol, C6-phenyl column; Supporting Information Figure S1), and the structure of each of the three peaks in the HPLC chromatogram was assigned based on their polarity and distinct UV−vis absorption in the range 350−600 nm (18). This general synthetic approach can be used to prepare a variety of amphiphilic C_{70} compounds, simply by replacing its glycolic acid residues with other polar groups.



Scheme 1. Synthesis of Amphiphilic Fullerene C_{70} ALM (the ALM Structure Represents Three Isomers)

Liposome Preparation. ALM was first formulated in liposomes with egg-PC (l-α-phosphatidylcholine) by the reverse-phase method, and the resulting suspension was extruded to obtain small vesicles (28, 29). ^{31}P NMR spectroscopy confirmed the formation of bilayer liposomes and ^{31}P spectrum of ALM-PC liposome (1 mg/mL ALM) shows a very sharp signal at 2.55 ppm, with a half line-width of 2.8 Hz, which is comparable to the corresponding values of liposomes made of only egg-PC (Supporting Information Figure S2) (30). The particle sizes of extruded (with 0.1 μm polycarbonate nucleopore membrane) liposomes were confirmed by DLS with an average diameter of 100 ± 20 nm (31). Intriguingly, the fullerene liposomes were dimensionally very stable. The amphipathic fullerene did not separate from the phospholipids during and after nucleopore extrusion. This was confirmed by buoyant density separation test under conditions (high-speed centrifugation at 18 000 *g* for 30 min.) where fullerenes not stably incorporated in bilayer membranes would separate from lipid vesicles and precipitate to the bottom of the 40% sucrose cushion. All fullerenes were found to stay on the top of sucrose solution after centrifugation, indicating that they remained tightly associated with lipids (Supporting Information Figure S3). The tight association between ALM and PC lipids was further confirmed by the observed coelution of ALM and egg-PC on a size exclusion column. The fact that ALM only did not form liposome and it needs the assistance of regular lipids to coassemble into liposomes also demonstrates the successful incorporation of ALM molecule in the bilayer structure formed by the auxiliary lipids (Supporting Information Figure S4). In fact, the ALM−liposome is stable for at least one year without noticeable precipitation or aggregation. The chemical stability of the fullerene compound in liposome formulations was also monitored by MALDI-MS, UV−vis, and HPLC after extracting fullerenes into organic solvents from aliquots of liposome samples, showing no decomposition or other structural changes. Next, we examined the ratio of fullerenes to lipids in the course of forming stable liposome and found that fullerene-to-lipid molar ratio could be as high as 1:1 (or mass ratio of roughly 2:1 or 65% fullerenes). In typical preparations, the fullerene concentration is 1.0 mg/mL liposome in phosphate buffered saline. ALM was also demonstrated to form liposomes in a similar fashion

with other lipids such as 1,2-dimyristoyl-*sn*-glycero-3-phosphocholine) (DMPC) and (1,2-distearoyl-*sn*-glycero-3-phosphocholine) (DSPC).

EPR Studies. Electron paramagnetic resonance (EPR) studies were conducted as described by Ali et al (25) to confirm that bipolarly functionalized C_{70} compounds were still capable of efficiently scavenging oxygen radicals (hydroxyl and superoxide radicals). Representative EPR spectra (Figure 2, insert) show typical HO· signals, as well as their quenching by ALM at four different concentrations. Figure 2 also shows the dose−response curve of hydroxyl radical-quenching by ALM solution in DMSO. As expected, ALM is a highly potent scavenger for hydroxyl radicals, significantly reducing HO· 4-fold at 10 μg/mL (6.7 μM). ALM also effectively quenched superoxide radicals to a slightly lesser extent. It is noteworthy to point out that ALM, due to its amphipathic nature, forms micelles in the assay media, and its antioxidative efficacy might be partially masked due to its limited access and interaction with free radicals generated in the media.

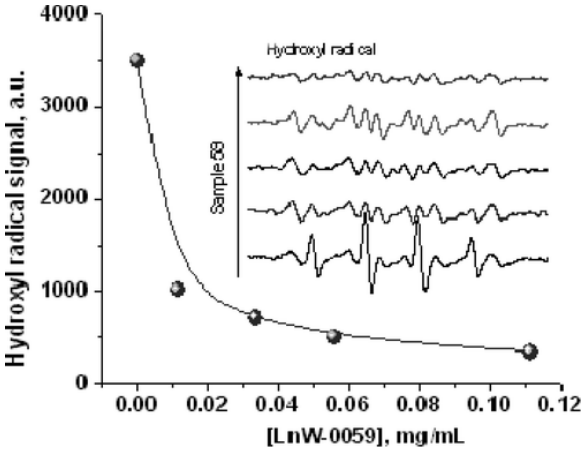


Figure 2. Hydroxyl radical quenching by ALM at four different concentrations. Insert shows EPR spectra of hydroxyl radicals generated via the Fenton reaction, with (top 4 curves) or without (bottom curve) the addition of a DMSO solution of ALM (LnW-0059) at 0.01 mg/mL, 0.03 mg/mL, 0.05 mg/mL, and 0.11 mg/mL. All observed signals were mixtures of DMPO−OH + DMPO−Me (Fenton products). (The DMPO-Me signal is attributable to radical reactions with DMSO).

Protection of Lipid Peroxidation. When lipid molecules, especially unsaturated lipids in cell membrane, are exposed to radicals such as hydroxyl radicals, highly reactive lipid species (lipid alkyl radicals and lipid peroxy radicals) are formed and the resulting lipid peroxidation can eventually cause membrane leakage and cellular dysfunction (32). Fullerenes formulated in liposome vesicles are particularly attractive for inhibiting lipid peroxidation. The protection effects of ALM liposome on hydroxyl radical-induced lipid peroxidation were therefore evaluated. The hydroxyl radicals were generated by the Fenton reaction as described above. A pH-sensitive dye 8-hydroxylpyrene-1,3,6-trisulfonic acid trisodium salt (HPTS) was encapsulated in the internal aqueous compartment of ALM−liposome and control liposome (without ALM) with a lower pH of 6.6 (23, 24). The outer bulk aqueous phase has a higher pH of 7.9. Upon membrane leakage caused by lipid peroxidation, the dye absorption ratio $A_{455\ nm}/A_{405\ nm}$ increases due to the rising pH, and a higher ratio $A_{455\ nm}/A_{405\ nm}$ indicates a greater extent of

membrane leakage and lipid peroxidation. Fullerenes have strong absorption in the range 400−450 nm; thus, the ALM content was kept very low at 1% to clearly monitor the spectral changes of the dye. In order to explicitly demonstrate the protection effects, both absorbance ratio ($A_{455\ nm}/A_{405\ nm}$) and absorbance difference ($A_{455\ nm} - A_{405\ nm}$) were plotted as a function of time ($t = 0$ when HO· generation reaction was initiated) (Figure 3). The membrane leakage in the control liposome was dramatic, but it was minimal in the ALM−liposome sample. Additional control experiments were also conducted, and the $A_{455\ nm}/A_{405\ nm}$ of HPTS was monitored in ALM−liposome or control liposome samples in the absence of the Fenton reagents. No noticeable changes in the absorption spectra of HPTS were observed for both samples, excluding the possibility that the control liposome is inherently leakier than the ALM-encapsulated liposome. These results clearly demonstrate the strong protection effects of ALM liposome against radical-induced peroxidation and membrane leakage.

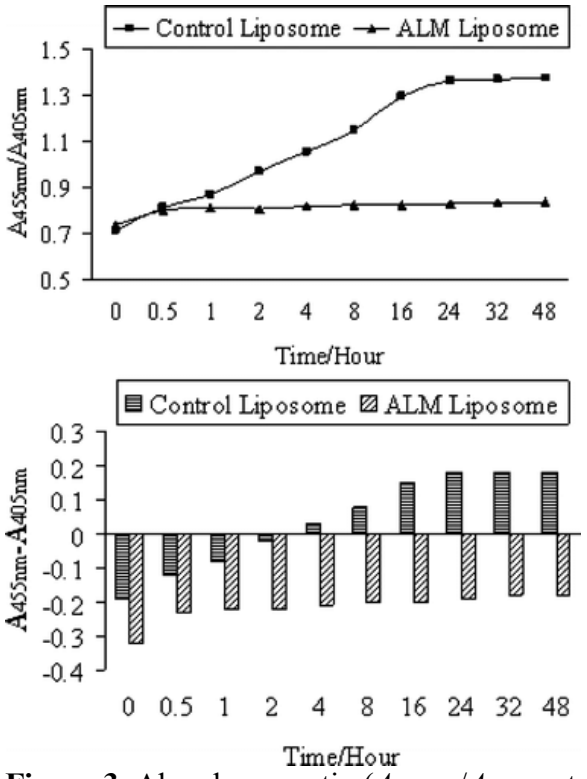


Figure 3. Absorbance ratio ($A_{455\ nm}/A_{405\ nm}$, top) and absorbance difference ($A_{455\ nm} - A_{405\ nm}$, bottom) of HPTS as a function of reaction time from when the Fenton reagents were added to the liposome samples. 1% fullerene was contained in ALM liposome. (1.0 mM $H_2O_2$and 0.05 mM Fe^{2+} ions of final concentrations).

In Vitro ROS Inhibition and Cytotoxicity. ALM liposome was also evaluated for its capability to quench extra cellular reactive oxygen species (ROS) release triggered by lipopolysaccharide (LPS) (33, 34). The monocyte cell line U937 used in this study is clinically relevant to atherosclerosis. The generation of foam cells from activated monocytes involves ROS overproduction and is a key inflammatory process in atherosclerotic plaque buildup (35). U937 monocytes, before LPS activation, were treated with a cell-permeable fluorogenic probe 2′,7′-dichlorodihydrofluorescein diacetate (DCFH-DA) (36). Following LPS activation, DCFH-DA underwent cellular hydrolysis and oxidation by ROS to generate the highly fluorescent 2′,7′-

dichlorofluorescein (DCF). As shown in Figure 4, ALM liposome inhibited cellular ROS release, while the control liposome (without ALM) did not. More than 80% ROS release was inhibited when the cells were treated with 6 μM ALM liposome samples, and even at 6 nM, the inhibition was over 20%. This suggests that the liposome formulation efficiently delivered amphiphilic fullerenes into cells and effectively exerted its anti-ROS efficacy. The liposomal ALM was also compared with a well-studied water-soluble C_{60} derivative-C_3 (six carboxyl groups—three malonic acids directly attached to a C_{60} cage) in this assay (9). As shown in Figure 4, ALM was 40−70% more potent than C_3 in scavenging cellular ROS when compared at equal molar concentrations. This could be explained by the difference in their dipole moments, structural dimension, and the resultant ability to intercalate in lipid bilayer and permeate cell membranes. Amphiphilic fullerene ALM has higher lipid/aqueous partition coefficient than C_3 in favor of cellular membrane permeation in addition to the potential endocytotic uptake of ALM liposome.

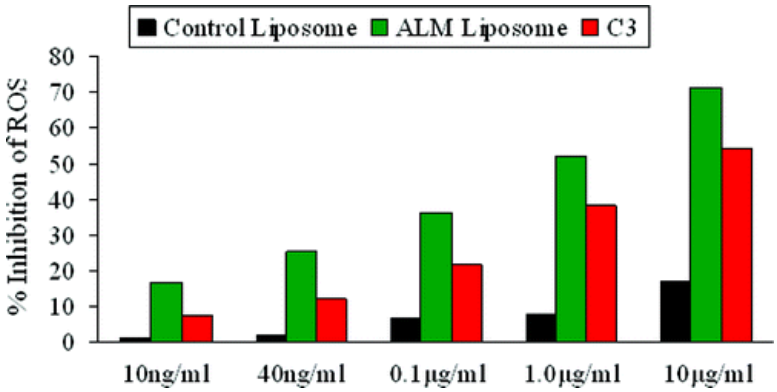


Figure 4. Inhibition of ROS in U937 monocytes by liposomes. For each concentration, the same volume of control liposome was used as the control. The fluorescence intensity was recorded and used as the measure to quantify ROS inhibition.

Finally, the cytotoxicity of the ALM liposome was examined. A number of factors including chemical structure, surface modification, water solubility, aggregation, particle size, and preparation procedures appear to have impacts on fullerene toxicity and behavior in biological systems (11, 37). In general, well-characterized fullerene derivatives with high solubility in buffer have little or no toxicities. We evaluated the cytotoxicity of ALM liposome with U937 monocytes, and ALM was found not cytotoxic to U937 cells when incubated with up to 67 μM (0.1 mg/mL) of ALM for 6 days. The cell viabilities were comparable for ALM-treated, vitamin E-treated, and untreated cells at all concentrations (Supporting Information Figure S5).

Conclusions

We have presented a novel fullerene delivery approach via liposomes enriched with amphiphilic C_{70} bisadducts that were designed to structurally mimic cellular membrane lipids. The choice of C_{70} along with its inherent bipolar bisaddition pattern represents a novel pathway to design amphiphilic fullerene compounds compatible for vesicular incorporation. The strong association between reported fullerenes and auxiliary lipids allow them to form dimensionally stable liposomes with as high as 65% (by weight) fullerene. By mimicking the structure of naturally occurring lipid molecules, this design overcomes several limitations in previously reported formulations including (1) low fullerene content of 3%−7% due to their use of underivatized

C_{60}(12, 13) or lipophilically functionalized C_{60}(38), structures of which are not dimensionally compatible with the polar head/lipophilic double-tail structure of lipids; and (2) damaged antioxidative bioactivity due to the multiple additions of six groups to C_{60} in an octahedral pattern where the spherical π-electron conjugation is interrupted leading to interconnected biphenyls (16, 39). As a drug delivery vehicle, the high fullerene loading capacity is very important, and it is advantageous especially for in vivo studies such as the delivery of fullerene to its intended region of action at sufficient concentrations with lower dose volumes. The vesicularly formulated fullerene ALM has been demonstrated as potent radical scavengers in three separate ROS-related experiment settings. In summary, this present approach provides a new way to deliver fullerenes to sites where their antioxidant properties can be exploited and provides a platform for synthesizing new fullerene-based therapeutics that not only retain their biological activity, but can also be delivered via liposome carriers.

Supporting Information

Additional information as described in the text and mass spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

Acknowledgment

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