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Synthesis and Characterization of Positively Charged Pentacationic [60]Fullerene Monoadducts for Antimicrobial Photodynamic Inactivation

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Abstract: We designed and synthesized two analogous pentacationic [60]fullerenyl monoadducts, C_{60}(>ME_{1}N_{6}C_{3}) (1) and C_{60}(>ME_{3}N_{6}C_{3}) (2), with variation of the methoxyethyleneglycol length. Each of these derivatives bears a well-defined number of cationic charges aimed to enhance and control their ability to target pathogenic Gram-positive and Gram-negative bacterial cells for allowing photodynamic inactivation. The synthesis was achieved by the use of a common synthon of pentacationic N,N′,N,N,N,N-hexapropyl-hexa(amoenoethyl)amine arm (C_{3}N_{6}+) having six attached propyl groups, instead of methyl or ethyl groups, to provide a well-balanced hydrophobic–hydrophilic character to pentacationic precursor intermediates and better compatibility with the highly hydrophobic C_{60} cage moiety. We demonstrated two plausible synthetic routes for the preparation of 1 and 2 with the product characterization via various spectroscopic methods.

Keywords: pentacationic C_{60} monoadducts; decacationic C_{60} monoadduct; N,N′,N,N,N,N-hexapropyl-hexa(amoenoethyl)amine; photosensitizer
1. Introduction

Broad-spectrum one-photon based photodynamic therapy (1γ-PDT)-mediated killing of pathogenic Gram-positive (e.g., Staphylococcus aureus) and Gram-negative (e.g., Escherichia coli) bacterial targets using a conventionally accessible light source is an emerging medical approach to treat infectious diseases, especially, those caused by multi-antibiotic-resistant bacteria [1–5]. The efficacy of 1γ-PDT depends on several parameters, including photophysical characteristics of the photosensitizer, the ability of the photosensitizer to target bacteria, the method of administration, and the availability of an appropriate light source. Fullerenes are highly photostable molecules suitable for single-dose multiple-treatments applications. Nearly quantitative efficiency of intersystem crossing from the excited singlet state of [60]fullerene (1C60*) to its triplet excited state (3C60*) readily allows intermolecular triplet energy transfer from 3C60* to molecular oxygen leading to the production of singlet oxygen (1O2) [6,7], which is highly reactive toward biological substrates producing subsequent cell damage. This photochemical mechanism serves as the basis of photodynamic cytotoxicity against pathogenic microorganisms, including multi-antibiotic-resistant bacteria. However, chemical functionalization of C60 is necessary to enhance its solubility in water. In general, attachment of multiple hydroxyl, carboxylic acid, and glycolic oxide addend groups may serve the purpose. Water-solubility of these derivatives increases as the number of hydrophilic groups increases, whether these functional groups are located in either the same addend group or different addend moieties. The latter case leads to the synthesis of fullerényl multiadducts that may change significantly the molecular orbital configuration of the fullerene cage and, thus, its HOMO–LUMO energy gap level and effectiveness in the production of 1O2. The 1γ-PDT efficiency can be optimized by performing only a limited number of addition reactions to the fullerényl olefinic bonds to preserve the low HOMO–LUMO energy gap level of the cage. This restriction suggests that [60]fullerene monoadducts using hydrophilic or amphiphilic groups would be suitable candidates. However, since only one addend group is able to be attached to the cage in a monoadducts, sufficient hydrophilicity is required to allow compatibility of the resulting derivative with water.

It has been demonstrated that polycationic photosensitizers exhibited high activity as 1γ-PDT agents for targeting and photokilling against both Gram-positive and Gram-negative bacterial species [8,9]. These reported findings revealed the importance of cell surface interactions between multicationic drug molecules and anionic peptide residues in the cell wall. Specifically, several factors including differences in physiology, cell wall, and cytoplasmic membrane structures between Gram-positive and Gram-negative bacteria [10–12] affect the properties of particular functional groups to be attached on the fullerene cage to allow effective targeting selectivity, drug-delivery, and photodynamic inactivation.

Accordingly, we considered the structural modification of C60 to allow the increase of its solubility in physiologic media and its compatibility in an environment of bacterial disease in tissue. This led to our design and synthesis of [60]fullerényl monoadducts bearing a well-defined high number of cationic charges that hitherto had remained challenging and has rarely been reported to date. In this paper, we describe a rational linkage of water-soluble quaternary alkylammonium multi-salts and ester-amide functional groups to a well-defined pentacationic arm together with an efficient synthetic method for its attachment on a C60 nanocage. The synthesis led to the preparation of new pentacationic [60]fullerene-based nano-photosensitizers 1 and 2, as shown in Schemes 1 and 2.
Scheme 1. The first synthetic steps of C_{60}(>ME_{1}N_{6}+C_{3}) 1 and C_{60}(>ME_{3}N_{6}+C_{3}) 2.

Reagents and conditions: i. Meldrum’s acid, 95 °C, 12 h; ii. NHS, DCC, THF, r.t., 1.0 day; iii. THF, r.t., 12 h; iv. CH_{3}–I, CHCl_{3}–DMF, 45 °C, 3.0 days; v. C_{60}, CBr_{4}, DBU, toluene–DMF, r.t., 10 h.

Scheme 2. The second synthetic steps of C_{60}(>ME_{1}N_{6}+C_{3}) 1 and C_{60}(>ME_{3}N_{6}+C_{3}) 2.

Reagents and conditions: vi. DCC, 2-methyl-2-propanol, CH_{2}Cl_{2}, r.t., 8.0 h; vii. C_{60}, DBU, toluene–ODCB, r.t., 12 h; viii. TFA, CH_{2}Cl_{2}, r.t., 15 h; ix. (a) SOCl_{2}, THF, reflux, 2.0 h; (b) N_{2}C_{2}–NH_{2}, 0 °C–r.t., 3.0 h; x. (a) aq. K_{2}CO_{3} (10%); (b) CH_{3}–I, CHCl_{3}–DMF, 45 °C, 3.0 days.
In these structures, arm moieties each bearing a high number of cationic charges and an amide moiety are capable of inducing the H-bonding in the vicinity of the fullerene cage.

2. Results and Discussion

Enhancement of the hydrophilicity of fullerene derivatives can be achieved by incorporation of the oligo(ethylene glycol) unit [13–15], an aminoacid moiety [16], or ionic functional groups [17–19] as addend attachments of C$_{60}$ cage. The resulting amphiphilic derivatives have been reported to undergo different forms of solid aggregation in aqueous solution if the hydrophilic moiety of the addend is insufficiently large to overcome the high hydrophobicity of the fullerene cage. To circumvent this solid aggregation problem, we undertook the effort to synthesize a well-defined water-soluble pentacationic $N,N',N,N,N,N$-hexapropyl-hexa(amoioethyl)amine arm moiety C$_3$N$_6^+$, as a charged C$_3$N$_6$ (6), with the number of charge being fixed at five per arm and used as the common synthon in the preparation of [60]fullerene monoadducts, as shown in Scheme 1. One example was given by the combination of a water-compatible ethylene glycol unit with a C$_3$N$_6^+$ arm to a single addend, such as the arm precursors ME$_1$N$_6^+$$C_3$ (9) and ME$_3$N$_6^+$$C_3$ (10), to enhance the water-solubility. Synthesis of 9 and 10 began with the reaction of either 2-methoxyethanol or triethylene glycol monomethyl ether with 2,2-dimethyl-1,3-dioxane-4,6-dione (3, Meldrum’s acid) at 90–95 °C for a period of 12 h to afford malonic acid methoxyethyleneglycol ester, ME$_1$ (4), or malonic acid methoxytriethyleneglycol ester, ME$_3$ (5), in 95 or 90% yield, respectively. Amidation reaction of 4 and 5 was carried out by the treatment with N-hydroxysuccinimide and $N,N'$-dicyclohexyl carbodiimide (DCC) in anyhydrous THF at ambient temperature over a period of 12 h, followed by the removal of insoluble byproduct of $N,N'$-dicyclohexyl urea and the further treatment with $N,N'$-hexapropyl-hexa(amoioethyl)amine, C$_3$N$_6$ (6), for an additional period of 12 h. These reactions resulted in the corresponding products of methoxyethyleneglycol-$[N,N',N,N,N,N$-hexapropyl-hexa(amoioethyl)-amino]malonamide ester, ME$_1$ (4), or malonic acid methoxytriethyleneglycol ester, ME$_3$ (5), in 95 or 90% yield, respectively. Amidation reaction of 4 and 5 was carried out by the treatment with N-hydroxysuccinimide and $N,N'$-dicyclohexyl carbodiimide (DCC) in anyhydrous THF at ambient temperature. Quaternization reaction of mono- and tri(ethoxylated) hexaaminomalonomamide precursors 7 and 8 using methyl iodide as the methylation agent at 45–50 °C for a period of 3.0 days afforded the corresponding methoxyethyleneglycol-$[N,N',N,N,N,N$-hexapropyl-hexa(amoioethyl)-amino]malonamide ester, ME$_1$N$_6$C$_3$ (7), and methoxy-tri(ethyleneglycol)-$[N,N',N,N,N,N$-hexapropyl-hexa(amoioethyl)-amino]malonamide ester, ME$_3$N$_6$C$_3$ (8), in 82 and 80% yield, respectively. Quaternization reaction of mono- and tri(ethoxylated) hexaaminomalonomamide precursors 7 and 8 using methyl iodide as the methylation agent at 45–50 °C for a period of 3.0 days afforded the corresponding methoxyethyleneglycol-$[N,N',N,N,N,N$-hexapropyl-hexa(amoioethyl)-amino]malonamide ester methyl quaternary ammonium salt, ME$_1$N$_6^+$$C_3$ (9), and its tri(ethoxylated) analogue ME$_3$N$_6^+$$C_3$ (10) in 94 and 92% yield, respectively. Attachment of a C$_{60}$ cage on the quaternary ammonium salts of malonamide was accomplished by the treatment of 9 and 10 in DMF with predissolved C$_{60}$ in toluene in the presence of 1,8-diazabiclo[5.4.0]-undec-7-ene (DBU) at ambient temperature for a period of 8.0 h. In this reaction, carbon tetrabromide was applied as the bromination agent for the replacement of malonyl $\alpha$-proton in situ. To minimize the possible formation of partial fullerenyl byproducts containing multiaddends, an excess amount (2.5 equiv.) of C$_{60}$ was applied. At the end of fullerenation, an excessive amount of C$_{60}$ molecules was recovered and removed by repeatedly washing the crude products with toluene until the observation of a clear toluene solution in washings. The reaction procedure led to the isolation of methoxyethyleneglycol-(20-oxo-4,7,10,13,16-pentapropyl-4,7,10,13,16,19-hexaaza-nonadecan-19-yl)[60]fullerenyl malonate quaternary methyl ammonium salt,
C_{60}(>ME_1N_6^+C_3) (1), and its tri(ethyleneglycolated) analogue C_{60}(>ME_3N_6^+C_3) (2) in 55 and 50% yield, respectively.

Alternatively, as shown in Scheme 2, (ethyleneglycolated)malonic acids 4 and 5 were converted to their corresponding tert-butyl(2-methoxyethyl)malonate ester, ME_1(t-C_4) (11), and its tri(ethyleneglycolated) analogue ME_3(t-C_4) (12) in 74 and 77% yield, respectively, by an esterification reaction with t-butyl alcohol in anhydrous dichloromethane (DCM) in the presence of N,N'-dicyclohexylcarbodiimide (DCC) at ambient temperature for a period of 8.0 h. Subsequent fullereny cyclopropanation reaction of 11 and 12 was carried out by treatment with [60]fullerene solution in a mixture of toluene and 1,2-dichlorobenzene in the presence of carbon tetrabromide and 1,8-diazabicyclo[5.4.0]-undec-7-ene (DBU) over a period of 12 h at room temperature. The products tert-butyl(2-methoxyethyl)[60]fullereryl malonate, C_{60}[>ME_1(t-C_4)] (13), and tert-butyl(methoxytriethyleneglycol)[60]fullereryl malonate, C_{60}[>ME_3(t-C_4)] (14), were purified by column chromatography [SiO_2, toluene−ethyl acetate (20:1) as eluent] as brown solids in 78 and 75% yield, respectively. Direct transamidation reaction of 13 and 14 with C_3N_6 was not successful owing to the complicated side-reaction arising from the attack of C_3N_6 on C_60 itself at elevated temperatures which is required for the effective transamidation. Therefore, we carried out the transformation of 13 and 14 to the corresponding methoxyethyleneglycol-(20-oxo-4,7,10,13,16-pentapropyl-4,7,10,13,16,19-hexaaza-nonadecan-19-yl)[60]fullereryl malonate 17, C_{60}(>ME_1N_6C_3), and its methoxytriethyleneglycol ester analogous 18, C_{60}(>ME_3N_6C_3), respectively, by the acid hydrolysis of 13 and 14 first to 2-[60]fullereryl-3-(2-methoxyethoxy)-3-oxopropanoic acid 15, C_{60}(>ME_1H), and its methoxytriethyleneglycol ester analogous 16, C_{60}(>ME_3H), respectively. The latter products were obtained as brown solids in yields of 89% and 87%, respectively. Conversion of 15 and 16 to their acid chloride intermediates was carried out by the reaction with thionyl chloride in THF. To minimize the amination of C_3N_6 on C_{60}, subsequent reaction with the acid chloride intermediate was performed at 0 °C to room temperature over a period of 3.0 h. A relatively pure C_{60}(>ME_1N_6C_3) 17 was obtained in 47% yield. It was accompanied with a small quantity of byproduct as a decarboxylated fullerene malonate-monoadduct that is removable. The stability of 17 and 18 in either solution or solid phase was found to be low owing to possible intermolecular complex formation between the hexaamine moiety and C_{60} cage giving insoluble aggregate solids. Therefore, compound 17 and 18 was quaternized to the protonated ammonium–trifluoroacetate salt C_{60}(>ME_1N_6^+C_3) (1′) and C_{60}(>ME_3N_6^+C_3) (2′), respectively, with trifluoroacetic acid in a short period of time immediately after the workup procedure and purification. Final synthesis of the products pentacationic methoxyethyleneglycol-(20-oxo-4,7,10,13,16-pentapropyl-4,7,10,13,16,19-hexaaza-nonadecan-19-yl)[60]fullereryl malonate 17, C_{60}(>ME_1N_6C_3), and its analogous methoxytriethyleneglycol ester C_{60}(>ME_3N_6C_3) (2), was carried out by the neutralization of 1′ and 2′ first with aqueous potassium carbonate in CHCl_3 as a biphase solution. Resulting [60]fullereryl malonates 17 and 18, respectively, were then transferred to a solvent mixture of anhydrous CHCl_3 and DMF (2:1) for methyl quaternization with an excess amount of iodomethane added portionwise over a period of 3.0 days at 45 °C to afford 1 and 2. Successful amidation conversion from malonic acid 5 to ME_3N_6C_3 was verified by the FT-IR spectrum of 8 (Figure 1a) showing two clear and strong vibrational carbonyl absorption bands centered at 1667 and 1736 cm\(^{-1}\) corresponding to malonylamide carbonyl [−NH-C(=O)−] and ester carbonyl (−C=O) moieties, respectively. In the same spectrum, IR peaks located at 2952, 2928, 2862, and 2805 cm\(^{-1}\)
were assigned to the stretching absorption bands of aliphatic \(-C-H\). Anti-symmetric deformations of \(-CH_3\) groups and scissor vibrations of \(-CH_2\) groups appeared as medium intensity bands centered around 1456 cm\(^{-1}\), while symmetric deformations of \(CH_3\) groups exhibited the absorption around 1379 cm\(^{-1}\) that overlaps with the \(-N-C-\) stretching vibration of amide \([-N-(C=O)-]\) bands at 1400 cm\(^{-1}\). A strong broad band centered at 1104 cm\(^{-1}\) was assigned to the stretching vibrations of \(-C-O-C-\) and \(-C-N-\) moieties. Methyl quaternization of 8, having tertiary penta(ethylamino) arms, to ME\(_3\)N\(_6\)\(^+\)C\(_3\) \(10\) with iodide salts showed retention of some of IR absorption bands (Figure 1b), except the shift of \(-NH-C(=O)-\) band to 1669 cm\(^{-1}\) and a new broad band at 947 cm\(^{-1}\), corresponding to the absorption of a number of quaternary \(-C-N^+–\) bonds. Formation of ME\(_3\)N\(_6\)\(^+\)C\(_3\)-attached C\(_{60}\) monoadduct was verified by the observation of a sharp characteristic fullerene half-cage absorption band of C\(_{60}(>\text{ME}_3\text{N}_6\text{C}_3)\) \(2\) at 524 cm\(^{-1}\) in the spectrum of Figure 1c. These results provided a good agreement of the product structure of \(2\). Similar infrared absorption bands of C\(_{60}(>\text{ME}_1\text{N}_6\text{C}_3)\) \(1\) were observed, except a relatively smaller \(-C-O-C–\) band than that of \(2\) centered at 1000–1200 cm\(^{-1}\).

Figure 1. FT-IR spectra of (a) ME\(_3\)N\(_6\)C\(_3\) \(8\), (b) ME\(_3\)N\(_6\)\(^+\)C\(_3\) \(10\), and (c) C\(_{60}(>\text{ME}_3\text{N}_6\text{C}_3)\) \(2\).

Mass spectroscopic data collection of both \(1\) and \(2\) was proven to be difficult due to their polycationic nature and facile fragmentations occurring at the conjunction of the C\(_{60}\) cage and the pentacationic malonate arm, giving mainly the highly detectable C\(_{60}\) ion mass fragment at \(m/z\) 721, as displayed in MALDI−TOF mass spectra using sinapic acid as the matrix. All fragmented high mass ions were very weak in intensity including peaks at \(m/z\) 1930 (M\(^+–\)I\(^–\)) (supporting information) and 2019 (M\(^H^+–\)I\(^–\)) as the molecular ion of \(1\) and \(2\), respectively. The most pronounced mass fragmentation ions at \(m/z\) 874 and 876 in both spectra of \(1\) and \(2\) were assigned to the substructure of C\(_{60}[>\text{H(C=O)NHCH}_2\text{CH}_3\text{N}^+\text{PrMe}_2]\), indicating a main malonylamide moiety being attached on a C\(_{60}\) cage, consistent with the [60]fullerenyl monoadduct structure.

In the case \(^1\)H-NMR spectroscopic analyses, we first well-characterized the arm structures ME\(_1\)(t-C\(_4\)) (11, Figure 2a) and ME\(_3\)(t-C\(_4\)) (12) by identification of all protons (H\(_a\), H\(_e\), H\(_f\), H\(_g\), and H\(_i\) indicated in Scheme 2) with their assignments to peaks shown in the spectra. Attachment of \(11\) on C\(_{60}\) leading to a monoadduct C\(_{60}[>\text{ME}_1\text{(t-C}_4)]\) (13) was evident by the disappearance of a H\(_a\) proton peak with the chemical shift at \(\delta\) 3.33. It was also accompanied with up-fielded shifts of two proton peaks to \(\delta\) 3.06 and 3.26, corresponding to the chemical shift of terminal methoxy protons H\(_g\) and ethylene oxide.
protons Hα in toluene-\(d_8\) from δ 3.34 and 3.56 of 11 in CDCl₃, respectively, reflecting partly the solvent effect. Hydrolysis of 13 to C₆₀(>ME₁H) (15) was also apparent by the loss of t-butyl protons at δ 1.55, as shown in Figures 2b and 2c, accompanied with down-fielded shifts of proton peaks (Hg, Hf, and Hα) to δ 3.34, 3.71, and 4.59, respectively, in THF-\(d_8\) showing a larger solvent effect. Monoadduct structures of 13 and 14 were also confirmed by the detection of well-defined characteristic fullerényl sp² carbon peaks in their \(^{13}\)C-NMR spectra (Figure 3b) showing a group of 26 and 27 peaks, respectively, each accounted for two carbons and a group of 6 single carbon peaks for 13 (two of these single carbon peaks may be derived from the slightly unsymmetrical environment around the malonate moiety) and 4 single carbon peaks for 14 in the region of δ 135–150, consistent with a \(C_v\) molecular symmetry for both 13 and 14. It also displayed two clear carbonyl carbon peaks at δ 163.45 (O=\(\text{C-O-}\)) and 161.86 (O=\(\text{C-O-}\)) in toluene-\(d_8\), for 13 and the corresponding peaks at δ 163.95 and 162.16 in CDCl₃ for 14. Evidence of the acid formation in the structure of 15 and C₆₀(>ME₃H) (16) was given by the solubility change and up-fielded shifts of the carbonyl chemical-shift to δ 161.13 (O=\(\text{C-OH}\)) and 161.62 (O=\(\text{C-O-}\)) in THF-\(d_8\)–CS₂ (2:1) for 15 (Figure 3c), partly due to the solvent effect. More clear changes of carbonyl carbon peak positions were observed for the case of 16 showing down-fielded shifts to δ 163.79 (O=\(\text{C-OH}\)) and 164.12 (O=\(\text{C-O-}\)) (Figure 3d) from those of 14 in the same solvent, consistent with the corresponding structural modification.

**Figure 2.** \(^{1}\)H NMR spectra of (a) 11 in CDCl₃, (b) 13 in toluene-\(d_8\), (c) 15 in THF-\(d_8\), (d) 1’ in CDCl₃–toluene-\(d_8\), and (e) 1 in DMSO-\(d_6\)–toluene-\(d_8\).
Figure 3. $^{13}$C-NMR spectra of (a) 13 in toluene-$d_8$; (b) 14 in CDCl$_3$; (c) 15 in THF-$d_8$–CS$_2$; (d) 16 in CDCl$_3$; and (e) 1$^\prime$ in CDCl$_3$.

In addition, the spectra of both compounds 15 and 16 displayed a group of 27 peaks each accounted for two sp$^2$ fullerenyl carbons and four single sp$^2$ carbon peaks in the region of $\delta$ 135–145 provided the further confirmation of a $C_v$ molecular symmetry of C$_{60}(>\text{ME}_1\text{H})$ and C$_{60}(>\text{ME}_3\text{H})$, respectively, as monoadducts without change during the chemical reaction.

Attachment of hexa(aminoethyl)amine $\text{C}_3\text{N}_6^+$ arm to the malonic acid moiety of C$_{60}(>\text{ME}_1\text{H})$ leading to the structure of C$_{60}(>\text{ME}_1\text{N}_6^+\text{C}_3)$ 1$^\prime$ and subsequently 1 was confirmed by the analyses of both infrared and $^1$H-NMR spectra. The latter of 1$^\prime$ showed proton peaks corresponding to the $\text{C}_3\text{N}_6^+$ arm moiety with overlap of a number of terminal ammonium-propyl $\alpha$-protons (H$_c$), $\alpha$-protons to amide group (H$_d$), glycol ether protons (H$_f$), and terminal methoxy protons (H$_g$) giving broad multiplet peaks in the region of $\delta$ 3.0–4.25 in CDCl$_3$–toluene-$d_8$ (Figure 2d). The second broad multiplet peaks in the region of $\delta$ 4.25–4.75 were assigned to ammonium-ethyl protons (H$_c^\prime$) and $\alpha$-protons to the ester group (H$_e$). In the case of 1, chemical shifts of similar groups of protons (H$_c$, H$_d$, H$_f$, and H$_g$) and (H$_c^\prime$, H$_e$, and ammonium-methyl protons H$_h$) were assigned to those of broad multiplet peaks at $\delta$ 3.0–3.75 and 3.75–4.5, respectively, in DMSO-$d_6$–toluene-$d_8$ (2:1), as shown in Figure 2(e). Interestingly, $^{13}$C-NMR spectrum of C$_{60}(>\text{ME}_1\text{N}_6^+\text{C}_3)$ 1$^\prime$ (Figure 3e) showed a group of 27 peaks each accounted for two sp$^2$ fullerenyl carbons and four single sp$^2$ carbon peaks (two of them having an identical chemical shift) in the region of $\delta$ 135–150 that provided a clear confirmation of a $C_v$ molecular symmetry of C$_{60}(>\text{ME}_1\text{N}_6^+\text{C}_3)$ monoadduct.

3. Experimental

3.1. Materials

The reagents 2-methoxyethanol, triethylene glycol monomethyl ether, 2,2-dimethyl-1,3-dioxane-4,6-dione (Meldrum’s acid), $N$-hydroxysuccinamide (NHS), $N,N'$-dicyclohexyl carbodiimide (DCC),
iodomethane, carbon tetrabromide (CBr₄), 1,8-diazabicyclo[5,4,0]-undec-7-ene (DBU), 2-methyl-2-propanol, trifluoroacetic acid (TFA), thionyl chloride (SOCl₂), K₂CO₃, γ-butyrolactone (GBL), BF₃·Et₂O, triethylamine, and pyridine were purchased from Aldrich Chemicals and used without further purification. Malonyl chloride was purchased from TCI America. A C₆₀ sample with a purity of 99.0% was used. Sodium sulfate was employed as a drying agent. Solvents were routinely distilled before use.

3.2. Spectroscopic Measurements

Infrared spectra were recorded as KBr pellets on a Thermo Nicolet Avatar 370 FT-IR spectrometer. ¹H-NMR and ¹³C-NMR spectra were recorded on a Bruker Avance Spectrospin-500 spectrometer. UV-Vis spectra were recorded on a Perkin Elmer Lambda 750 UV-Vis-NIR Spectrometer. MALDI-mass spectra were recorded on a WATERS Micromass MALDI-TOF mass spectrometer. Elemental analysis was taken by Galbraith Laboratories, Inc. (Knoxville, TN, USA).

3.3. Synthetic Procedures

3.3.1. Synthesis of Malonic Acid Methoxyethyleneglycol Ester, ME₁ (4)

A mixture of 2-methoxyethanol (1.0 g, 13.1 mmol) and 2,2-dimethyl-1,3-dioxane-4,6-dione (3, Meldrum’s acid, 1.9 g, 13.2 mmol) was stirred under an Ar atmosphere over a period of 12 h at 95 °C. The reaction mixture was cooled to room temperature, treated with aqueous sodium carbonate solution (5%), and washed with diethyl ether. The resulting aqueous layer was subsequently treated with dil. HCl (2.0 N) and extracted with ethyl acetate (50 mL). The ethyl acetate solution was dried over Na₂SO₄ and concentrated on rotary evaporator to give the product ME₁ (4) in 95% yield (2.0 g). Spectroscopic data: FT-IR (KBr) \( \nu_{\text{max}} 3060 \) (w), 2880 (w), 2814 (w), 1727 (vs), 1458 (w), 1399 (m), 1318 (s), 1251 (s), 1134 (vs), 1039 (m), 952 (w), 848 (s), and 755 (m) cm⁻¹; ¹H-NMR (500 MHz, CDCl₃, ppm) \( \delta 10.60 \) (s, br, 1H), 4.31 (t, \( J = 4.63 \) Hz, 2H), 3.45 (s, 2H), and 3.38 (s, 3H).

3.3.2. Synthesis of Malonic Acid Methoxytriethyleneglycol Ester, ME₃ (5)

A mixture of triethylene glycol monomethyl ether (1.0 g, 6.1 mmol) and 2,2-dimethyl-1,3-dioxane-4,6-dione (3, Meldrum’s acid, 0.9 g, 6.2 mmol) was stirred under Ar atmosphere over a period of 12 h at 90 °C. The reaction mixture was cooled to room temperature, treated with aqueous sodium carbonate solution (5%), and washed with diethyl ether. The resulting aqueous layer was subsequently treated with dil. HCl (2.0 N) and extracted with ethyl acetate (50 mL). The ethyl acetate solution was dried over Na₂SO₄ and concentrated on rotary evaporator to give the product ME₃ (5) in 90% yield (1.37 g). Spectroscopic data: FT-IR (KBr) \( \nu_{\text{max}} 3056 \) (w), 2880 (w), 2817 (w), 1728 (vs), 1455 (w), 1394 (m), 1318 (s), 1251 (s), 1134 (vs), 1098 (vs), 1034 (m), 952 (w), 847 (s), and 753 (m) cm⁻¹; ¹H-NMR (500 MHz, CDCl₃, ppm) \( \delta 9.65 \) (s, br, 1H), 4.32 (t, \( J = 4.50 \) Hz, 2H), 3.70 (t, \( J = 4.50 \) Hz, 2H), 3.65–3.55 (m, 8H), 3.42 (s, 3H), and 3.41 (s, 2H).
3.3.3. Synthesis of Methoxyethyleneglycol-[N,N',N,N,N,N-hexapropyl-hexa(aminopropyl)amino]-malonamide Ester, ME1N6C3 (7)

A mixture of malonic acid methoxyethyleneglycol ester 4 (0.5 g, 3.08 mmol), N-hydroxy succinamide (0.35 g, 3.08 mmol), and N,N'-dicyclohexyl carbodiimide (DCC, 0.63 g, 4.0 mmol) in anhydrous tetrahydrofuran (20 mL) were stirred under N₂ atmosphere over a period of 12 h at ambient temperature. The resulting white solids of N,N'-dicyclohexyl urea byproduct were filtered off and the filtrate was taken into a second round-bottom flask containing N,N',N,N,N,N-hexapropyl-hexa(aminopropyl)amine 6 (1.49 g, 3.08 mmol). The mixture was stirred under N₂ atmosphere for an additional period of 12 h. At the end of the reaction, the solvent was removed on rotavap. To this residue, ice-cold hexane–dichloromethane (1:1, 15 mL) was added followed by filtration to remove further white solids of N-hydroxy succinimide. The filtrate was washed with aqueous sodium carbonate (5%) solution (10 mL). The organic layer was then dried and concentrated to give ME1N6C3 (7) as yellow liquid in 82% yield (1.59 g). Spectroscopic data: ESI–MS (rel. intensity) m/z 568, 570 (M–CH₃OCH₂CH₂, 75%), 571, 629 (M⁻, 630 (MH⁺, 100%), 631, 646, 666, 670, 688, 700, 715 [MH⁺+CH₂CH₂N(CH₂CH₂CH₃), 48%], 716, 755, 757, 772, 773, 775, 800 (MH⁺+2[CH₂CH₂N(CH₂CH₂CH₃)], 15%), 801, 832, 860, 1150, 1210, 1212 (the dimer mass–CH₃OCH₂), 1236, and 1252 (from the dimer ion mass); FT-IR (KBr) $\nu_{\text{max}}$ 3259 (w), 2956 (vs), 2932 (s), 2872 (m), 2808 (m), 1742 (s), 1660 (s), 1550 (w), 1459 (s), 1273 (m), 1128 (m), 1074 (s), 1031 (m), and 742 (w) cm⁻¹; ¹H-NMR (500 MHz, CDCl₃, ppm) $\delta$ 4.29 (t, $J$ = 4.25 Hz, 2H), 3.61 (t, $J$ = 4.25 Hz, 2H), 3.40 (s, 3H), 3.34–3.32 (m, 4H), 2.38–2.57 (m, 30H), 1.47–1.44 (m, 2H), and 0.90–0.87 (t, $J$ = 7.15 Hz, 18H); ¹³C-NMR (500 MHz, CDCl₃, ppm) $\delta$ 168.78 (–C=O), 164.65 (O=C–NH–), 70.06, 64.15, 58.90, 57.35, 57.29, 57.13, 56.83 (4C), 56.72, 56.55, 53.65, 53.00, 52.81, 52.58, 52.46, 52.00, 41.60, 37.58, 20.41, 20.39, 20.37, 20.32 (2C), 20.18, 11.90 (3C), 11.87 (2C), and 11.74.

3.3.4. Synthesis of Methoxy-tri(ethyleneglycol)-[N,N',N,N,N,N-hexapropyl-hexa(aminopropyl)amino]-malonamide Ester, ME3N6C3 (8)

A mixture of malonic acid methoxytriethyleneglycol ester 5 (1.0 g, 4.0 mmol), N-hydroxy succinamide (0.45 g, 4.0 mmol), and N,N'-dicyclohexyl carbodiimide (0.82 g, 4.0 mmol) in anhydrous tetrahydrofuran (30 mL) were stirred under N₂ atmosphere for a period of 12 h at ambient temperature. The resulting white solids of N,N'-dicyclohexyl urea byproduct were filtered off and the filtrate was taken into a second round-bottom flask containing N,N',N,N,N,N-hexapropyl-hexa(aminopropyl)amine 6 (1.94 g, 3.9 mmol). The mixture was stirred under N₂ atmosphere for an additional period of 12 h. At the end of the reaction, the solvent was removed on rotavap. To this residue, ice-cold hexane–dichloromethane (1:1, 20 mL) was added followed by filtration to remove white solids of N-hydroxy succinimide. The filtrate was washed with aqueous sodium carbonate (5%) solution (10 mL). The organic phase was then dried and concentrated to give ME3N6C3 (8) as yellow liquid in 80% yield (2.29 g). Spectroscopic data: ESI–MS (rel. intensity) m/z 512, 568 [M–CH₃O(CH₂CH₂O)₂CH₂, 65%], 660 (M–CH₃OCH₂CH₂, 55%), 716, 718 (MH⁺, 100%), 734, 776, 803 [MH⁺+CH₂CH₂N(CH₂CH₂CH₃) from the dimer mass, 46%], 819, 860, 888 (MH⁺+2[CH₂CH₂N(CH₂CH₂CH₃)] from the dimer mass, 8%), 944, 951, 1008, 1090, 1226 (the dimer
mass–[MeO(EG)₃-CO], 3%), 1238, 1282, 1340, and 1434 (the dimer ion); FT-IR (KBr) $\nu_{\text{max}}$ 3328 (w), 2952 (m), 2928 (m), 2862 (m), 2805 (m), 1736 (vs), 1667 (s), 1533 (m), 1456 (m), 1400 (m), 1379 (m), 1245 (m), 1104 (vs), 1032 (w), 938 (w), and 732 (m) cm⁻¹; ¹H-NMR (500 MHz, CDCl₃, ppm) δ 4.22 (t, J = 4.68 Hz, 2H), 3.65 (t, J = 4.68 Hz, 2H), 3.58–3.60 (m, 6H), 3.48 (t, J = 4.60 Hz, 2H), 3.32 (s, 5H), 3.26 (s, br, 2H), 2.31−2.48 (m, 30H), 1.40−1.38 (m, 12H), and 0.82−0.79 (t, J = 6.95 Hz, 18H); ¹³C-NMR (500 MHz, CDCl₃, ppm) δ 168.83 (–C=O), 164.70 (O=C–NH–), 71.86 (2C), 70.53, 70.51, 68.74, 64.30, 58.95, 57.32 (2C), 57.14, 56.83 (4C), 56.72, 56.53, 53.64, 53.41, 52.98 (2C), 52.80, 52.45, 41.54, 37.55, 20.40, 20.37, 20.31 (3C), 20.24, 11.91 (3C), 11.88 (2C), and 11.76.

3.3.5. Synthesis of Methoxyethyleneglycol-[N,N′,N,N,N,N-hexapropyl-hexa(aminooethyl)amino]-malonamide Ester Quaternary Methyl Ammonium Salt, ME₁N₆⁺C₃ (9)

A solution of malonamide ester 7 (1.0 g, 1.6 mmol) in anhydrous chloroform–DMF (10:1) was added iodomethane (6.0 mL, excess, in portions) and stirred at 45 °C for a period of 3.0 days. At the end of quaternization, the solvent was evaporated to afford ME₁N₆⁺C₃ (9) in 94% yield (2.0 g). Spectroscopic data: FT-IR (KBr) $\nu_{\text{max}}$ 3444 (s), 3236 (m), 2968 (vs), 2937 (vs), 2877 (m), 1735 (s), 1667 (s), 1536 (m), 1459 (vs), 1331 (w), 1245 (m), 1104 (m), 948 (m), 872 (w), 750 (vs), and 661 (m) cm⁻¹; ¹H-NMR (500 MHz, DMSO-d₆, ppm) δ 3.80−4.25 (m, br, 16H), 2.90−3.80 (m, br, 49H), 1.50−1.80 (m, br, 12H), and 0.85−0.99 (m, br, 18H); ¹³C-NMR (500 MHz, DMSO-d₆, ppm) δ 168.09 (–C=O), 166.69 (O=C–NH–), 79.90, 79.70, 70.01, 64.28 (4C), 63.59 (5C), 58.54, 55.54 (4C), 53.96 (2C), 49.37 (3C), 48.85 (2C), 42.62, 16.27 (2C), 15.95 (4C), 10.94 (2C), 10.82 (2C), and 10.72 (2C) (one peak is covered by DMSO peaks). Anal. Calcd for C₃₄H₇₂N₆O₄·4.5CH₃I·2H₂O (based on 90% quaternization on average): C, 35.47; H, 6.92; N, 6.45; I, 43.80; O, 7.36%. Found: C, 34.72; H, 6.82; N, 6.46; I, 42.31%.

3.3.6. Synthesis of Methoxy-tri(ethyleneglycol)-[N,N′,N,N,N,N-hexapropyl-hexa(aminooethyl)amino]-malonamide Ester Quaternary Methyl Ammonium Salt, ME₃N₆⁺C₃ (10)

A solution of malonamide ester 8 (0.50 g, 0.70 mmol) in anhydrous chloroform–DMF (10:1) was added iodomethane (3.0 mL, excess, in portions) and stirred at 45 °C for a period of 3.0 days. At the end of quaternization, the solvent was evaporated to afford ME₃N₆⁺C₃ (10) in 92% yield (0.92 g). Spectroscopic data: ESI–MS (rel. intensity) m/z 448 (100%), 503, 588 (40%), 731 (M⁺−5I–4CH₃, 6%), 760, 815, 872, 873 (M⁺−4I–3CH₃, 8%), 930, 1014, 1016 (M⁺−3I–2CH₃, 13%), 1074, 1099, 1157 (M⁺−2I–CH₃, 37%), 1198, 1216, 1299, 1300 (M⁺−I, 22%), 1385, 1391, 1392, 1442, 1443, and 1444 (M⁺+H₂O); FT-IR (KBr) $\nu_{\text{max}}$ 3436 (vs), 3255 (m), 3066 (m), 2968 (s), 2935 (s), 2877 (m), 1736 (s), 1665 (s), 1634 (s), 1545 (w), 1459 (s), 1383 (w), 1351 (w), 1332 (w), 1271 (w), 1200 (m), 1110 (s), 1034 (m), 950 (m), 877 (w), 757 (w), and 600 (m) cm⁻¹; ¹H-NMR (500 MHz, DMSO-d₆, ppm) δ 3.80−4.25 (m, br, 16H), 2.90−3.80 (m, br, 49H), 1.50−1.80 (m, br, 12H), and 0.85−0.99 (m, br, 18H); ¹³C-NMR (500 MHz, DMSO-d₆, ppm) δ 168.13 (–C=O), 166.69 (O=C–NH–), 71.72, 70.23, 70.18, 70.03, 68.57, 63.56 (9C), 54.79 (6C), 49.05 (5C), 42.62, 16.18 (2C), 15.97 (4C), 10.95 (2C), 10.82 (3C), and 10.70 (one peak is covered by DMSO peaks). Anal. Calcd for C₃₈H₈₀N₆O₄·4CH₃I·3H₂O (based on 80% quaternization on average): C, 37.67; H, 7.38; N, 6.28; I, 37.91; O, 10.76%. Found: C, 36.10; H, 7.03; N, 6.81; I, 37.90%.
3.3.7. Synthesis of Pentacationic Methoxyethyleneglycol-(20-oxo-4,7,10,13,16-pentapropyl-4,7,10,13,16,19-hexaaza-nonadecan-19-yl)[60]fullerenyl Malonate Quaternary Methyl Ammonium Salt, C_{60}(>\text{ME}_1\text{N}_6^+\text{C}_3) (1)

Finely divided [60]fullerene (0.94 g, 1.30 mmol, more than two-fold excess to allow the formation of monoadduct only) was taken into a round bottom flask and added anhydrous toluene (700 mL) under nitrogen. The solution was stirred for 12 h at ambient temperature to ensure complete dissolution of C_{60}. To the resulting purple-colored solution added carbon tetrabromide (0.19 g, 0.57 mmol) followed by a solution of the compound 9 (0.70 g, 0.52 mmol) in anhydrous DMF (100 mL). The solution mixture was stirred for an additional 30 min and added slowly 1.8-diazabicyclo[5.4.0]-undec-7-ene (DBU, 0.17 g, 1.15 mmol) over a period of 45 min. The color of solution slowly turns into brown in a reaction period of 8.0 h. The solution was then concentrated on rotavap to roughly 100 mL. Upon the addition of methanol to this concentrated solution, the crude product was precipitated as brown solids which were collected via centrifugation. Unreacted C_{60} in the crude solids was removed by repeated washings with toluene (5 × 100 mL) until no color in the washing solution or filtrate. The remaining product of C_{60}(>\text{ME}_1\text{N}_6^+\text{C}_3) (1) was obtained as brown solids in 55% yield (0.59 g, after recovered C_{60}). Spectroscopic data: FT-IR (KBr) \(\nu_{\text{max}}\) 3383 (vs), 2963 (m), 2932 (m), 2870 (m), 2814 (w), 1739 (s), 1686 (s), 1625 (s), 1455 (vs), 1426 (s), 1373 (w), 1240 (w), 1067 (s), 1031 (s), 947 (m), 728 (m), 575 (m), and 525 (vs, a characteristic band of C_{60} monoadduct) cm\(^{-1}\); UV-Vis (DMF, cutoff at 268 nm, 2.0 × 10\(^{-3}\) M) \(\lambda_{\text{max}}\) 323 nm (shoulder peak); \(^1\)H-NMR [500 MHz, DMSO-\text{d}_6–toluene-\text{d}_8 (2:1), ppm] \(\delta\) 3.80–4.25 (m, br, 16H), 2.90–3.80 (m, br, 39H), 1.50–1.80 (m, br, 12H), and 0.88–0.99 (m, br, 18H). We found that electronic interferences of iodide anions in a high quantity with the fullerene cage or possible partial electron-transfer events prohibited the detection of fullerenyl carbon peaks (in low signal intensity).

3.3.8. Synthesis of Pentacationic Methoxy-tri(ethyleneglycol)-(20-oxo-4,7,10,13,16-pentapropyl-4,7,10,13,16,19-hexaaza-nonadecan-19-yl)[60]fullerenyl Malonate Methyl Quaternary Ammonium Salt, C_{60}(>\text{ME}_3\text{N}_6^+\text{C}_3) (2)

Finely divided [60]fullerene (1.0 g, 1.40 mmol, more than two-fold excess to allow the formation of monoadduct only) was taken into a round bottom flask and added anhydrous toluene (700 mL) under nitrogen. The solution was stirred for 12 h at ambient temperature to ensure complete dissolution of C_{60}. To the resulting purple-colored solution added carbon tetrabromide (0.17 g, 0.51 mmol) followed by a solution of compound 10 (0.65 g, 0.45 mmol) in anhydrous DMF (100 mL). The solution mixture was stirred for an additional 30 min of stirring and added slowly 1.8-diazabicyclo[5.4.0]-undec-7-ene (DBU, 0.15 g, 0.98 mmol) over a period of 45 min. The color of solution slowly turns into brown in a reaction period of 8 h. The solution was then concentrated on rotavap to roughly 100 mL. Upon the addition of methanol to this concentrated solution, the crude product was precipitated as brown solids which were collected via centrifugation. Unreacted C_{60} in the crude solids was removed by repeated washings with toluene (5 × 100 mL) until no color in the washing solution or filtrate. The remaining product of C_{60}(>\text{ME}_3\text{N}_6^+\text{C}_3) (2) was obtained as brown solids in 50% yield (0.343 g, after recovered C_{60}). Spectroscopic data: FT-IR (KBr) \(\nu_{\text{max}}\) 3433 (vs), 3262 (s), 2963 (m), 2925 (m), 2868 (m), 2809
(w), 1736 (s), 1736 (m), 1630 (s), 1459 (s), 1384 (w), 1197 (m), 1107 (s), 1071 (s), 938 (m), 757 (w), and 525 (s, a characteristic band of C₆₀ monoadduct) cm⁻¹; UV-Vis (DMF, cutoff at 268 nm, 2.0 × 10⁻⁵ M) \( \lambda_{\text{max}} \) 323 nm (shoulder peak); \(^1\)H-NMR [500 MHz, DMSO-\( d_6 \)-toluene-\( d_8 \) (2:1), ppm] \( \delta \) 3.80–4.20 (m, br, 16H), 2.90–3.80 (m, br, 47H), 1.50–1.75 (m, br, 12H), and 0.88–0.99 (m, br, 18H). We found that electronic interferences of iodide anions in a high quantity with the fullerene cage or possible partial electron-transfer events prohibited the detection of fullerenyl carbon peaks (in low signal intensity).

3.3.9. Synthesis of tert-Butyl(2-methoxyethyl)malonate, ME\(_t\)(t-C₄) (11)

A mixture of malonic acid methoxyethylene glycol ester 4 (1.0 g, 6.16 mmol), 2-methyl-2-propanol (0.54 g, 7.39 mmol), and \( N,N' \)-dicyclohexyl carbodiimide (DCC, 1.27 g, 6.16 mmol) in anhydrous dichloromethane (20 mL) were stirred under atmospheric pressure of N\(_2\) over a period of 8.0 h at ambient temperature. The resulting white solid of \( N,N' \)-dicyclohexyl urea was filtered and the filtrate was washed with aqueous sodium carbonate solution (5%, 10 mL). The organic layer was then dried over sodium sulfate and concentrated on rotavap to give ME\(_t\)(t-C₄) (11) in 74% yield (1.0 g) as light yellow liquid. Spectroscopic data: FT-IR (KBr) \( \upsilon_{\text{max}} \) 2980 (w), 2930 (w), 2880 (w), 2824 (w), 1748 (s), 1726 (vs), 1455 (w), 1406 (w), 1393 (w), 1368 (m), 1330 (m), 1281 (m), 1250 (m), 1199 (m), 1127 (vs), 1037 (s), 966 (m), 864 (m), 838 (m), 759 (w), and 738 (w) cm⁻¹; \(^1\)H-NMR (500 MHz, CDCl₃, ppm) \( \delta \) 4.27 (t, \( J = 3.94 \) Hz, 2H), 3.56 (t, \( J = 3.94 \) Hz, 2H), 3.34 (s, 3H), 3.29 (s, 2H, \( H_\alpha \)), and 1.43 (s, 9H).

3.3.10. Synthesis of tert-Butyl(methoxy-triethyleneglycol)malonate, ME\(_t\)(t-C₄) (12)

A mixture of malonic acid methoxy triethylene glycol ester 5 (3 g, 11.98 mmol), 2-methyl-2-propanol (1.06 g, 14.38 mmol), and \( N,N' \)-dicyclohexyl carbodiimide (2.47 g, 11.98 mmol) in anhydrous dichloromethane (20 mL) were stirred under atmospheric pressure of N\(_2\) over a period of 8.0 h at ambient temperature. The resulting white solid of \( N,N' \)-dicyclohexyl urea was filtered and the filtrate was washed with aqueous sodium carbonate solution (5%, 10 mL). The organic layer was then dried over sodium sulfate and concentrated on rotavap to give ME\(_t\)(t-C₄) (12) in 77% yield (2.85 g) as light yellow liquid. Spectroscopic data: FT-IR (KBr) \( \upsilon_{\text{max}} \) 2973 (w), 2930 (w), 2876 (w), 2817 (w), 1748 (s), 1727 (vs), 1455 (w), 1393 (w), 1368 (m), 1330 (m), 1282 (m), 1250 (m), 1198 (m), 1134 (vs), 1104 (vs), 1040 (m), 966 (m), 864 (m), 759 (w), and 735 (w) cm⁻¹; \(^1\)H-NMR (500 MHz, CDCl₃, ppm) \( \delta \) 4.26 (t, \( J = 4.50 \) Hz, 2H), 3.68 (t, \( J = 4.50 \) Hz, 2H), 3.63 (m, 6H), 3.52 (t, \( J = 4.50 \) Hz, 2H), 3.35 (s, 3H), 3.29 (s, 2H, \( H_\alpha \)), and 1.44 (s, 9H).

3.3.11. Synthesis of tert-Butyl(2-methoxyethyl)[60]fullereryl Malonate, C\(_{60}\)[>ME\(_t\)(t-C₄)] (13)

Finely divided [60]fullerene (1.23 g, 1.70 mmol) was taken into a round bottom flask and added anhydrous toluene (850 mL) and 1,2-dichlorobenzene (30 mL) under nitrogen. The solution was stirred for 1.0 h at ambient temperature to ensure complete dissolution of C\(_{60}\). To the resulting purple-colored solution was added carbon tetrabromide (0.50 g, 1.51 mmol) followed by a solution of tert-butyl(2-methoxyethyl)malonate (11, 0.30 g, 1.37 mmol) in anhydrous toluene (10 mL). The solution mixture was stirred for an additional 30 min and added slowly 1.8-diazabicyclo[5.4.0]-undec-7-ene
(DBU, 0.44 g, 2.88 mmol) over a period of 1.0 h. The color of solution slowly turned into brown in a reaction period of 12 h. The solution was then concentrated on a rotavap. The resulting crude product was purified using column chromatography with silica gel as the stationary phase and toluene–ethyl acetate (20:1) as eluent, giving the isolation of tert-butyl(2-methoxyethyl)[60]fullerenyl malonate (13), C60[>ME2(t-C4)], as brown solids in 78% yield (1.00 g). Spectroscopic data: FT-IR (KBr) νmax 3442 (br, s), 2972 (w), 2917 (w), 2873 (w), 2814 (w), 1739 (vs), 1645 (m), 1426 (m), 1390 (w), 1366 (m), 1268 (s), 1232 (vs), 1179 (m), 1151 (s), 1110 (m), 1059 (m) 1026 (m), 828 (w), 738 (w), 704 (w), 577 (m), 551 (m), and 525 (vs, a characteristic band of C60 monoadduct) cm⁻¹; ¹H-NMR (500 MHz, toluene-d₈, ppm) δ 4.28 (t, J = 4.55 Hz, 2H), 3.26 (t, J = 4.55 Hz, 2H), 3.06 (s, 3H), and 1.55 (s, 9H); ¹³C-NMR (500 MHz, toluene-d₈, ppm) δ 163.45 (O=C–O–tert-butyl), 161.86 (O=C–O–), 145.89 (2C), 145.53 (2C), 145.22 (2C), 145.13 (2C), 145.06 (3C), 144.95 (2C), 144.93 (2C), 144.60 (2C), 144.59 (2C), 144.46 (3C), 144.45 (4C), 143.71 (2C), 143.68 (2C), 142.91 (C), 142.89 (C), 142.83 (2C), 142.81 (3C), 142.80 (3C), 142.74 (2C), 142.03 (2C), 142.02 (2C), 141.76 (2C), 141.74 (2C), 140.74 (2C), 140.68 (2C), 139.37 (2C), 138.93 (2C), 84.13, 72.07 (fullerenyl sp³ carbons, 2C), 69.74, 65.49, 58.00, 53.45, and 27.49 (3C).

3.3.12. Synthesis of tert-Butyl(methoxy-triethyleneglycol)[60]fullerenyl Malonate, C60[>ME3(t-C4)] (14)

Finely divided [60]fullerene (1.86 g, 2.59 mmol) was taken into a round bottom flask and added anhydrous toluene (850 mL) and 1,2-dichlorobenzene (50 mL) under nitrogen. The solution was stirred for 1.0 h at ambient temperature to ensure complete dissolution of C60. To the resulting purple-colored solution was added carbon tetrabromide (0.75 g, 2.27 mmol) followed by a solution of tert-butyl(methoxy-triethyleneglycol)malonate 12 (0.63 g, 2.07 mmol) in anhydrous toluene (10 mL). The solution mixture was stirred for an additional 30 min and added slowly 1.8-diazabicyclo[5.4.0]-undec-7-ene (DBU, 0.66 g, 4.35 mmol) over a period of 1.0 h. The color of solution slowly turned into brown in a reaction period of 12 h. The solution was then concentrated on rotavap and the resulting crude product was purified by column chromatography with silica gel as the stationary phase and toluene–ethyl acetate (9:1) as eluent to afford C60[>ME3(t-C4)] as brown solids in 75% yield (1.60 g). Spectroscopic data: FT-IR (KBr) νmax 3421 (br, s), 2967 (w), 2914 (w), 2864 (w), 2814 (w), 1740 (s), 1634 (m), 1456 (m), 1426 (m), 1392 (m), 1368 (m), 1269 (s), 1253 (s), 1226 (s), 1180 (m), 1154 (s), 1108 (m), 1029 (m), 845 (m), 737 (m), 702 (m), 669 (m), 576 (m), 550 (m), and 525 (vs) cm⁻¹; ¹H-NMR (500 MHz, CDCl₃, ppm) δ 4.65 (t, J = 4.60 Hz, 2H), 3.90 (t, J = 4.60 Hz, 2H), 4.03 (t, J = 4.60 Hz, 2H), 3.73 (t, J = 4.60 Hz, 2H), 3.55–3.68 (m, 4H), 3.41 (s, 3H), and 1.70 (s, 9H); ¹³C-NMR (500 MHz, CDCl₃, ppm) δ 163.95 (O=C–O–tert-butyl), 162.16 (O=C–O–), 145.61 (2C), 144.41 (2C), 145.29 (2C), 145.25 (4C), 145.22 (2C), 145.16 (3C), 144.85 (2C), 144.71 (C), 144.69 (3C), 144.66 (2C), 144.57 (4C), 143.89 (3C), 143.09 (2C), 143.08 (2C), 143.01 (4C), 142.99 (2C), 142.97 (2C), 142.23 (2C), 142.21 (2C), 141.91 (2C), 141.90 (2C), 140.94 (2C), 140.89 (2C), 139.11 (2C), 138.92 (2C), 85.16, 71.95 (fullerenyl sp³ carbons, 2C), 71.84, 70.68, 70.67, 70.65, 68.84, 66.07, 59.10, 53.06, and 28.07 (3C).
3.3.13. Synthesis of 2-[60]Fullerenyl-3-(2-methoxyethoxy)-3-oxopropanoic Acid, C_{60}(> ME_1H) (15)

The compound of [60]fullerenyl malonate 13 (0.5 g, 0.64 mmol) was taken into a round bottom flask containing anhydrous dichloromethane (50 mL) and purged with N\textsubscript{2} for 15 minutes at ambient temperature. To this reaction mixture was added trifluoroacetic acid (30 mL, excess) and stirred for overnight at room temperature. At the end of the reaction, dichloromethane was removed on rotavap. Additional dichloromethane (3 × 15 mL) was added and removed on rotavap in order to fully eliminate an excessive amount of trifluoroacetic acid. The resulting residue was then washed with diethyl ether (2 × 15 mL) to afford C\textsubscript{60}(> ME_1H) (15) as brown solids in 89\% yield (0.50 g). Spectroscopic data: FT-IR (KBr) $\nu_{\text{max}}$ 3670 (br, s), 2977 (w), 2917 (w), 2878 (w), 2814 (w), 1792 (w), 1750 (s), 1708 (s), 1681 (m), 1541 (w), 1427 (m), 1390 (w), 1366 (m), 1267 (s), 1250 (s), 1231 (s), 1186 (m), 1114 (w), 1059 (w) 1020 (w), 864 (w), 743 (w), 701 (m), 572 (m), 552 (m), and 525 (vs, a characteristic band of C\textsubscript{60} monoadduct) cm\textsuperscript{-1}; $^{1}$H-NMR (500 MHz, THF-$d_8$, ppm) $\delta$4.59 (t, $\textbf{J}_1= 4.50$ Hz, 2H), 3.71 (t, $\textbf{J}_1= 4.50$ Hz, 2H), and 3.34 (s, 3H); $^{13}$C-NMR [500 MHz, THF-$d_8$–CS\textsubscript{2} (2:1), ppm] $\delta$161.62 (O=\textbf{C}–O–), 161.13 (O=\textbf{C}–OH), 144.54 (2C), 144.06 (2C), 143.53 (2C), 143.39 (2C), 143.26 (2C), 143.25 (2C), 143.19 (2C), 143.16 (2C), 142.91 (C), 142.85 (2C), 142.78 (C), 142.73 (2C), 142.70 (2C), 142.53 (4C), 141.99 (2C), 141.95 (2C), 141.14 (C), 141.12 (C), 141.04 (4C), 140.98 (2C), 140.31 (4C), 140.07 (2C), 139.95 (2C), 138.89 (2C), 138.87 (2C), 137.87 (2C), 136.76 (2C), 70.48 (fullerenyl sp\textsuperscript{3} carbons, 2C), 68.14, 63.98, 56.30, and 51.46

3.3.14 Synthesis of 2-[60]Fullerenyl-3-(methoxy-triethyleneglycol)-3-oxopropanoic Acid, C_{60}(> ME_3H) (16)

The compound of [60]fullerenyl malonate 14 (0.75 g, 0.73 mmol) was taken into a round bottom flask containing anhydrous dichloromethane (50 mL) and purged with N\textsubscript{2} for a period of 15 minutes at ambient temperature. To this reaction mixture was added trifluoroacetic acid (50 mL) and stirred for overnight at room temperature. At the end of the reaction, dichloromethane was removed on rotavap. Additional dichloromethane (3 × 20 mL) was added and removed on rotavap in order to fully eliminate an excessive amount of trifluoroacetic acid. The resulting residue was then washed with diethyl ether (3 × 20 mL) to afford C\textsubscript{60}(> ME_3H) (16) as brown solids in 87\% yield (0.62 g). Spectroscopic data: FT-IR (KBr) $\nu_{\text{max}}$ 3673 (br, s), 2917 (w), 2894 (w), 2870 (w), 2814 (w), 1788 (w), 1741 (vs), 1578 (w), 1532 (w), 1426 (m), 1383 (w), 1266 (m), 1230 (m), 1203 (m), 1180 (w), 1095 (m), 1060 (w) 845 (w), 698 (m), 579 (m), 549 (m), and 525 (vs) cm\textsuperscript{-1}; $^{1}$H-NMR (500 MHz, CDCl\textsubscript{3}, ppm) $\delta$ 4.70 (t, $\textbf{J}_1= 4.55$ Hz, 2H), 3.95 (t, $\textbf{J}_1= 4.55$ Hz, 2H), 3.80 (m, 6H), 3.76 (t, $\textbf{J}_1= 4.60$ Hz, 2H), and 3.59 (s, 3H); $^{13}$C-NMR (500 MHz, CDCl\textsubscript{3}, ppm) $\delta$ 164.12 (O=\textbf{C}–O–), 163.79 (O=\textbf{C}–OH), 145.57 (2C), 145.52 (2C), 145.33 (3C), 145.32 (3C), 145.22 (4C), 145.15 (3C), 144.84 (2C), 144.75 (C), 144.68 (4C), 144.57 (2C), 144.54 (2C), 143.90 (2C), 143.88 (2C), 143.04 (3C), 142.99 (4C), 142.96 (2C), 142.23 (3C), 142.01 (2C), 141.97 (2C), 140.93 (3C), 140.92 (3C), 139.36 (2C), 138.90 (2C), 72.19, 71.88 (fullerenyl sp\textsuperscript{3} carbon, 2C), 70.89, 70.64, 70.33, 69.70, 68.34, 65.99, 58.78, and 52.51.
3.3.15. Synthesis of Methoxyethyleneglycol-(20-oxo-4,7,10,13,16-pentapropyl-4,7,10,13,16,19-hexaaza-nonadecan-19-yl)[60]fullerenyl Malonate, C_{60}(>ME_{1}\text{N}_{6}\text{C}_3) (17) and C_{60}(>\text{ME}_{1}\text{N}_{6}^{+}\text{C}_3) (1')

The compound of 2-[60]fullerenyl-3-(2-methoxyethoxy)-3-oxopropanoic acid (15) (0.15 g, 0.17 mmol) was taken into a round bottom flask containing anhydrous tetrahydrofuran (20 mL). To this reaction mixture was added thionyl chloride (0.03 g, 2.55 mmol) under N₂ atmosphere and refluxed for a period of 2.0 h. An excessive amount of thionyl chloride was removed on rotavap. Fresh anhydrous tetrahydrofuran (20 mL) was added. To this reaction solution was added slowly N,N',N,N,N,N-hexapropyl-hexa(aminoethyl)amine (6) (0.08 g, 0.17 mmol) at 0 °C. It was warmed gradually to room temperature and stirred at this temperature for a period of 3.0 h. The resulting solution was concentrated on rotavap with the residue washed sequentially with hexane (10 mL), methanol (2 × 10 mL), and toluene (3 × 10 mL) to fully remove unreacted N,N',N,N,N,N-hexapropyl-hexa(aminoethyl)amine and decarboxylated C₆₀ byproducts. A relatively pure C₆₀(>ME₁N₆C₃) (17) was obtained in 47% yield (0.11 g). It was subsequently treated with CF₃COOH to result in pentacationic quaternary ammonium−trifluoroacetate salt, C₆₀(>ME₁N₆+C₃) (1'), specifically, for NMR measurements.

Spectroscopic data of the compound 17: FT-IR (KBr) νmax 3670 (br, s), 2977 (w), 2917 (w), 2878 (w), 2814 (w), 1792 (w), 1750 (s), 1708 (s), 1681 (m), 1541 (w), 1427 (m), 1390 (w), 1366 (m), 1267 (s), 1250 (s), 1231 (s), 1186 (m), 1114 (w), 1059 (w), 1020 (w), 864 (w), 743 (w), 701 (m), 572 (m), and 525 (vs, a characteristic band of C₆₀ monoadduct) cm⁻¹. Spectroscopic data of the compound 1': ¹H-NMR [500 MHz, CDCl₃–toluene-d₈–TFA (3:1:1), ppm] δ 4.22–4.68 (m, br, 2H), 3.90–4.05 (m, br, 2H), 3.22–3.75 (m, br, 35H), 1.28–1.36 (m, br, 12H), and 0.97 (m, br, 18H); ¹³C-NMR [500 MHz, CDCl₃–toluene-d₈–TFA (3:1:1), ppm] δ 167.72 (O=\text{C–O}–), 166.46 (O=\text{C–NH}–), 148.00 (2C), 145.54 (2C), 145.30 (2C), 145.29 (2C), 145.14 (2C), 145.02 (2C), 144.73 (4C), 144.68 (4C), 144.53 (2C), 143.98 (2C), 143.77 (2C), 143.27 (2C), 143.11 (2C), 143.04 (2C), 143.01 (2C), 142.98 (C), 142.87 (2C), 142.44 (2C), 142.22 (2C), 142.12 (2C), 142.01 (2C), 141.17 (2C), 140.98 (2C), 140.51 (2C), 137.92 (4C), 136.50 (2C), 70.47, 70.23 (fullerenyl sp² carbon, 2C), 70.08, 69.73, 64.65, 64.40, 58.94, 58.68, 38.43, 31.84, 22.04, 21.40, 16.66, and 10.10 (quaternary aminocarbon peaks were low in intensity).


A solution of [60]fullerenyl malonate quaternary ammonium–trifluoroacetate salt 1' (100 mg) in chloroform (50 mL) was neutralized with aqueous potassium carbonate (10%, 50 mL). The resulting [60]fullerenyl malonate 17 was then dissolved in a mixture of anhydrous chloroform (30 mL) and dimethylformamide (15 mL). To this reaction, an excess amount of iodomethane was added in several portions over the reaction period and stirred at 45 °C for 3.0 days. At the end of the reaction, the solvent was removed on rotavap to yield pentacationic C₆₀(>ME₁N₆^+C₃) (1). Spectroscopic data: MALDI–TOF–MS (sinapic acid as the matrix, rel. intensity) m/z 673 (20%), 697 (50%), 721 (C₆₀H⁺, 100%), 734 (80%), 746 (15%), 761 (10%), 772 (10%), 874 [C₆₀(H(C=O)NHCH₂CH₂N⁺-propylMe₂), 20%], 1442 [(C₆₀H)²⁺ cluster], 1565, 1634, 1709, 1769, 1851, 1930 (M⁺–I); FT-IR (KBr) νmax 3688
(br, s), 2918 (s), 2870 (m), 2840 (m), 2807 (w), 1784 (w), 1736 (vs), 1663 (s), 1574 (w), 1433 (m), 1383 (w), 1252 (w), 1187 (m), 1163 (s), 1126 (m), 1090 (m), 1031 (s), 842 (w), 762 (w), 704 (w), 661 (w), 569 (w), and 524 (vs, a characteristic band of C$_{60}$ monoadduct) cm$^{-1}$; UV-Vis (DMF, cutoff at 268 nm, 2.0 $\times$ 10$^{-5}$ M) $\lambda_{\text{max}}$ 323 nm (shoulder peak); $^1$H-NMR [500 MHz, DMSO-$d_6$–toluene-$d_8$ (2:1), ppm] $\delta$ 3.80–4.25 (m, br, 16H), 2.90–3.80 (m, br, 39H), 1.50–1.80 (m, br, 12H), and 0.88–0.99 (m, br, 18H). We found that electronic interferences of iodide anions in a high quantity with the fullerene cage or possible partial electron-transfer events prohibited the detection of fullerenyl carbon peaks (in low signal intensity).

3.3.17. Synthesis of Pentacationic Methoxy-tri(ethylene glycol)-(20-oxo-4,7,10,13,16-pentapropyl-4,7,10,13,16,19-hexaaza-nonadecan-19-yl)[60]fullerenyl Malonate Methyl Quaternary Ammonium Salt, C$_{60}$(>ME$_3$N$_6^+$C$_3$) (2)

Synthesis of the compound 2 was carried out by using a similar procedure as that of 1 except methoxytriethylene glycol ester was applied instead. Spectroscopic data: MALDI–TOF–MS (sinapic acid as the matrix, rel. intensity) $m/z$ 698 (10%), 721 (C$_{60}$H$_{2}^+$, 100%), 735 (C$_{60}$H$_3^+$, 20%), 749, 773, 782, 789, 809, 874 [C$_{60}$(H(C=O)NHCH$_2$CH$_2$N$^-$-propylMe$_2$)], 914, 940, 995, 1027, 1054, 1278 (w), 1395 (w), 1417 (vw), 1499 (vw), 1792 (vw), and 2019 (vw, MH$^+$–I$^-$); FT-IR (KBr) $\nu_{\text{max}}$ 3424 (vs), 2967 (m), 2925 (m), 2874 (w), 2824 (w), 1738 (s), 1681 (s), 1628 (s), 1545 (vs), 1429 (s), 1383 (m), 1064 (s), 1028 (s), 941 (m), 727 (m), 572 (m), and 524 (vs, a characteristic band of C$_{60}$ monoadduct) cm$^{-1}$; UV-vis (DMF, cutoff at 268 nm, 2.0 $\times$ 10$^{-5}$ M) $\lambda_{\text{max}}$ 323 nm (shoulder peak); $^1$H-NMR [500 MHz, DMSO-$d_6$–toluene-$d_8$ (2:1), ppm] $\delta$ 3.80–4.20 (m, br, 16H), 2.90–3.80 (m, br, 47H), 1.50–1.75 (m, br, 12H), and 0.88–0.99 (m, br, 18H). We found that electronic interferences of iodide anions in a high quantity with the fullerene cage or possible partial electron-transfer events prohibited the detection of fullerenyl carbon peaks (in low signal intensity).

4. Conclusions

We have designed and synthesized two analogous pentacationic [60]fullerenyl monoadducts, C$_{60}$(>ME$_1$N$_6^+$C$_3$) (1) and C$_{60}$(>ME$_3$N$_6^+$C$_3$) (2), with variation of the methoxyethylene glycol length. Each of these derivatives bears a well-defined number of cationic charges aimed to enhance and control their ability to target pathogenic Gram-positive and Gram-negative bacterial cells. The intrinsic nature of the high charge number and increased water-solubility of the precursor arm intermediates hindered the efficiency of their reactions with a highly hydrophobic C$_{60}$ cage having low compatibility in polar solvents. Furthermore, consecutive ethylamino group linkage in a structure of N,N,N,N,N,N-hexapropyl-hexa(amoeth)ylamine (C$_3$N$_6$) largely increased its electron-donating capability that gave complication in forming an insoluble partial charge-transfer complex with C$_{60}$ during the reaction and workup procedures. After many attempts, we found a circumventive solution by the use of partially quaternized C$_3$N$_6$ prior to the reaction with C$_{60}$ coupled with the modification of C$_3$N$_6$ arm using propyl groups, instead of methyl or ethyl groups, to provide a well-balanced hydrophobicity–hydrophilicity character of pentacationic precursor intermediates and better compatibility with the C$_{60}$ cage moiety.
Supplementary Materials


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References and Notes


*Sample Availability*: Samples of the compounds 1 and 2 may be available from the authors.

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