Triazenes as a Stable Diazonium Source for Use in Functionalizing Carbon Nanotubes in Aqueous Suspensions

Jared L. Hudson, Huahua Jian, Ashley D. Leonard, Jason J. Stephenson, and James M. Tour*

Departments of Chemistry and Mechanical Engineering and Materials Science, and The Smalley Institute for Nanoscale Science and Technology, Rice University, MS 222, 6100 Main Street, Houston, Texas 77005

Received January 4, 2006. Revised Manuscript Received March 28, 2006

Organic triazene compounds are stable precursors to diazonium salts for functionalizing single-wall carbon nanotubes (SWNTs) in aqueous media. This method is particularly useful when a target molecule has functionality that will not tolerate diazotization conditions. We illustrate this by detailing the synthesis of a biotin-containing triazene followed by reaction with SWNTs.

Introduction

Diazonium chemistry is a known method to functionalize carbon nanotubes in an efficient manner with a variety of techniques developed to exploit the reactivity of diazonium compounds.[1] The high reactivity, while good for the functionalization process, is a potential problem in synthesis since some diazonium species have a short shelf life and decompose under reaction conditions. They are also a potential laboratory hazard since diazonium salts can be shock-sensitive and obtaining them in pure form by crystallization can be difficult.[2] Formation of diazonium salts in situ from aniline precursors is one method developed to avoid the direct use and long-term storage of diazonium compounds.[1] Unfortunately, no in situ method exists for the functionalization of carbon nanotubes in aqueous surfactant suspension. This paper describes the use of organic triazene compounds as stable precursors[3] to diazonium salts for functionalizing single-wall carbon nanotubes (SWNTs) in aqueous media. We also highlight the utility of the triazene functionality as a precursor to unstable diazonium salt species.

Results and Discussion

We achieved the triazene-based functionalization in a sodium dodecyl sulfate (SDS) suspension of SWNTs.[4] The neat triazene (adding an organic solvent solution of the triazene to the aqueous SWNT suspension produced inferior results) was added to an aqueous suspension of SWNTs and subsequently a film formed on the water. Upon adjustment to pH 2 with 6 M HCl, the film disappeared, apparently dissolving as the triazene was converted to the water-soluble diazonium salt. After the organic layer dissolved, the suspension was adjusted to pH 10 with 6 M NaOH to complete the reaction (Scheme 1). The mechanism of this functionalization has been discussed previously;[5] it is thought that functionalization initially occurs via the injection of an electron from a SWNT into the aryldiazonium salt, releasing N_2 and forming a reactive aryl radical that then reacts with the SWNT to form a new SWNT−arene bond. The reaction filtrate was analyzed by GC-MS and was found to contain no evidence of radical recombination products. This lends support to the proposed mechanism which requires close proximity of the diazonium salt to the nanotube for the requisite electron injection followed quickly by coupling with the SWNT.

The process was also used as a route to make more complex diazonium precursors in a convergent manner. This method is crucial for synthesis of triazene molecules that have nitrogen-containing moieties, such as biotin, due to their propensity to form *N*-nitroso species under standard reaction conditions.[6] Making the triazene separately and coupling it to the molecule of interest via an amide bond allows *N*-nitroso formation to be circumvented. Triazene **10** (Scheme 2) was coupled to the *N*-hydroxysuccinimide ester of biotin to form the biotinamide **11a** containing a terminal triazene which could then be attached to SWNTs using the method described above to yield **11b**.

Compound **10** provides a convenient synthetic handle to introduce the triazene moiety into many different molecules. Since the triazene functionality is more robust than a diazonium species, characterization of the final product is possible and greater flexibility in designing a synthesis is

* To whom correspondence should be addressed. E-mail: tour@rice.edu.

(1) (a) Dyke, C. A.; Tour, J. M. *J. Am. Chem. Soc.* **2003**, *125*, 1156. (b) Bahr, J. L.; Tour, J. M. *Chem. Mater.* **2001**, *13*, 3823. (c) Bahr J. L.; Yang J.; Kosynkin D. V.; Bronikowski M. J.; Smalley R. E.; Tour J. M. *J. Am. Chem. Soc.* **2001**, *123*, 6536. (d) Dyke, C. A.; Tour, J. M. *Chem. Eur. J.* **2004**, *10*, 812. (e) Dyke, C. A.; Tour, J. M. *Nano Lett.* **2003**, *3*, 1215. (f) Hudson, J.; Tour J. M. *J. Am. Chem. Soc.* **2004**, *126*, 11158. (g) Strano, M. S.; Dyke, C. A.; Usrey, M. L.; Barone, P. W.; Allen, M. J.; Shan, H.; Kittrell, C.; Hauge, R. H.; Tour, J. M.; Smalley, R. E. *Science* **2003**, *301*, 1519.

(2) Ullrich, R.; Grewer, T. *Thermochem. Acta* **1993**, *225*, 201.

(3) (a) Braese, S. *Acc. Chem. Res.* **2004**, *37*, 805. (b) Hwang, J.-J.; Tour, J. M. *Tetrahedron* **2002**, *58*, 10387. (c) Jian, H.; Tour, J. M. *J. Org. Chem.* **2005**, *70*, 3396. (d) Chen, B.; Flatt, A. K.; Jian, H.; Hudson J. L.; Tour, J. M. *Chem. Mater.* **2005**, *17*, 4832. (e) Flatt, A. K.; Chen, B.; Tour, J. M. *J. Am. Chem. Soc.* **2005**, *127*, 8918.

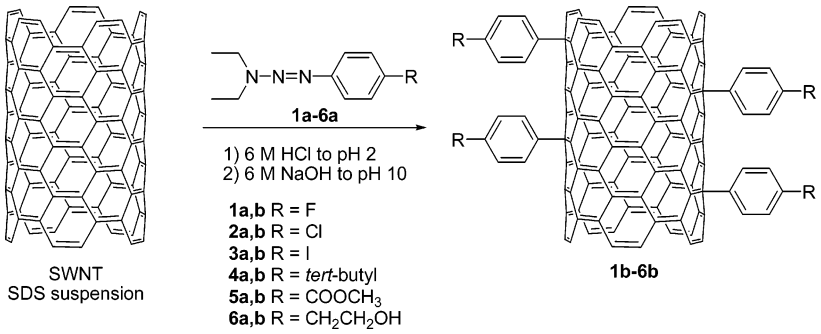
(4) Moore, V. C.; Strano, M. S.; Haroz, E. H.; Hauge, R. H.; Smalley, R. E.; Schmidt, J.; Talmon, Y. *Nano Lett.* **2003**, *3*, 1379.

(5) Dyke, C. A.; Stewart, M. P.; Maya, F.; Tour, J. M. *SynLett* **2004**, 155.

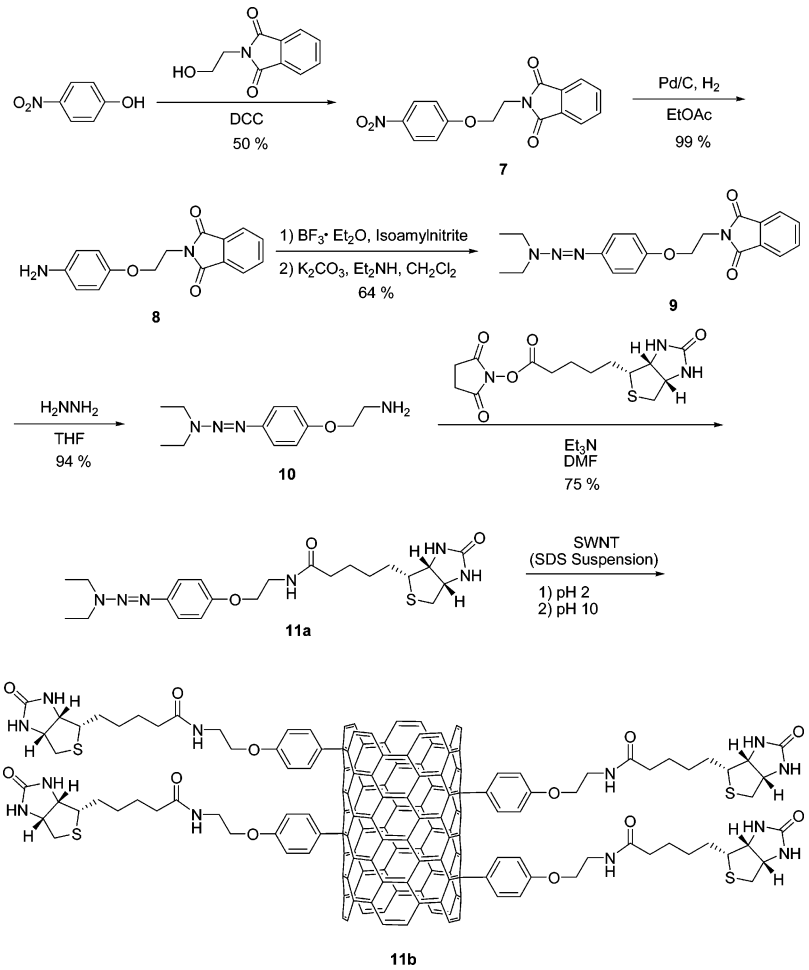
(6) Olah, G. A.; Olah, J. A.; Overchuk, N. A. *J. Org. Chem.* **1965**, *30*, 3373.

10.1021/cm060020l CCC: $33.50
Published on Web 05/04/2006

Scheme 1. Functionalization of SWNTs by Organic Triazenes



Scheme 2. Synthesis of Biotin-Functionalized SWNTs



available. We chose to use the coupling of **10** to biotin to highlight its potential uses in biological applications; however, this method could be exploited to make diazonium precursors for applications in sensors, drug delivery, or medical diagnostics.

Characterization. Figure 1A shows the characteristic van Hove singularities of the SDS/SWNTs used as starting material.[7] Figure 1B shows the loss of those transitions in product **2b**, a confirmation of covalent functionalization.[1,8] The loss of van Hove singularities was characteristic of all the products obtained (**1b**−**6b** and **11b**). Likewise, in Figure 1C, the Raman spectrum[9] of the starting SDS suspension of SWNTs shows a very small disorder mode (D-band) at 1290 cm^{-1}. In Figure 1D, the functionalized material displays a significant increase in the disorder mode relative to the large tangential mode (G-band), consistent with a high degree of functionalization.[8] Similarly, the Raman resonance enhancement seen in Figure 1C is suppressed after functionalization

(7) O'Connell, M. J.; Bachilo, S. M.; Huffman, C. B.; Moore, V. C.; Strano, M. S.; Haroz, E. H.; Rialon, K. L.; Boul, P. J.; Noon, W. H.; Kittrell, C.; Ma, J.; Hauge, R. H.; Weisman, R. B.; Smalley, R. E. *Science* **2002**, *297*, 593.

(8) (a) Bahr, J. L.; Tour, J. M. *J. Mater. Chem.* **2002**, *12*, 1952. (b) Bahr, J.; Yang, J.; Kosynkin, D. V.; Bronikowski, M. J.; Smalley, R. E.; Tour, J. M. *J. Am. Chem. Soc.* **2001**, *123*, 6536. (b) Dyke, C. A.; Tour, J. M. *J. Phys. Chem. A* **2004**, *108*, 11151.

(9) Sample morphology can have an effect on radial breathing mode intensities of the Raman bands of SWNTs. See (a) Baik, S.; Usrey, M.; Rotkina, L.; Strano, M. *J. Phys. Chem. B* **2004**, *108*, 15560. (b) Heller, D. A.; Barone, P. W.; Swanson, J. P.; Mayrhofer, R. M.; Strano, M. S. *J. Phys. Chem. B* **2004**, *108*, 6905. (c) Dyke, C. A.; Stewart, M. P.; Tour, J. M. *J. Am. Chem. Soc.* **2005**, *127*, 4497.

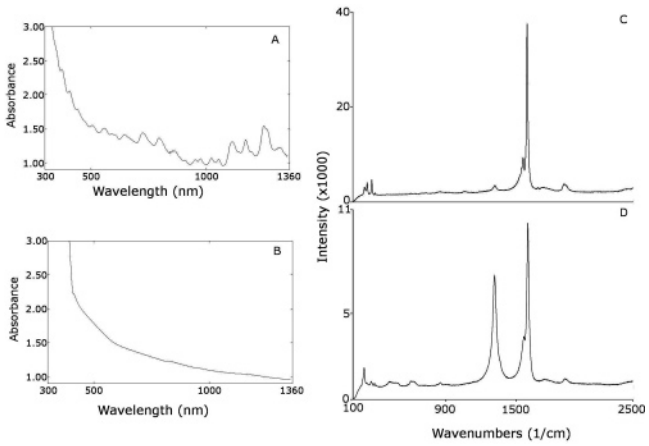


Figure 1. Absorption spectra of (A) SWNT in SDS suspension and (B) **2b** in DMF. Raman spectra (solid, median scan of five different areas per sample, 633 nm) of (C) SWNTs and (D) **2b**.

(Figure 1D), consistent with covalent attachment.[8] The ratios of the Raman D- to G-band intensities are shown in Table 1. Thermogravimetric (TG) analyses were carried out (10 °C/min to 850 °C, under Ar) with products **1b**−**6b** and **11b** (Table 1).

These results show a reasonable degree of tube coverage, though somewhat lighter than coverage seen in prior work with diazonium salts on aqueous suspensions.[1e] These results also highlight the fact that Raman spectroscopy is not a reliable tool in evaluating the degree of functionalization in a quantitative sense, especially when comparing different functionalities.[9] The method should only be used to roughly evaluate the relative degree of coverage when the same method of functionalization and the same functionality is being studied.

Atomic force microscopy (AFM) analysis (Figure 2) of product **4b** showed the characteristic unbundled, individual functionalized SWNTs with diameters consistent with individuals. The functionalized SWNTs were bundle-free throughout their entire lengths.

Table 1. TG Analytical Results Showing Total Mass Loss and Calculated Number of SWNT Carbons to Which a Functional Group Has Been Attached, along with the Intensity Ratio of the D to G Band in the Raman Spectra[a]

product	mass loss (%)	functional group coverage	Raman D/G ratio
1b	22	1 in 28 carbons	0.36
2b	17	1 in 44 carbons	0.72
3b	16	1 in 91 carbons	0.65
4b	49	1 in 11 carbons	0.42
5b	9	1 in 114 carbons	0.56
6b	39	1 in 16 carbons	0.52
11b	56	1 in 24 carbons	0.38

[a] Total mass loss was attributed to functional groups covalently attached to the sidewall. With use of the mass loss and the molecular weight of the functional group fragment, the number of moles of functional group present were calculated. The residual mass was attributed to pristine SWNT, which was used to determine the mequiv of SWNT carbons present. With the moles of both functional groups present and SWNT carbons, the functional group-to-SWNT-carbon ratio was calculated.[8]

The AFM data corroborated with transmission electron microscopy (TEM) (Figure 3) that showed the presence of individual SWNTs with a characteristic roughened surface, which has been attributed to the aryl moieties attached to the tube wall.[1e]

Compound **1b** was analyzed by XPS to further confirm the presence and degree of functional groups on the SWNT wall by extrapolation from the F content: atomic concentration C 95.38, N 1.44, F 3.18. Figure 4 shows the XPS spectra. Using the relative amount of C and F present in the sample and normalizing for F, we find that there are 30 C atoms per 1 F atom. If we assume that all the C present in the sample is either from the SWNT or from the functional group appended to the side wall and subtract 6 Cs (attributed to

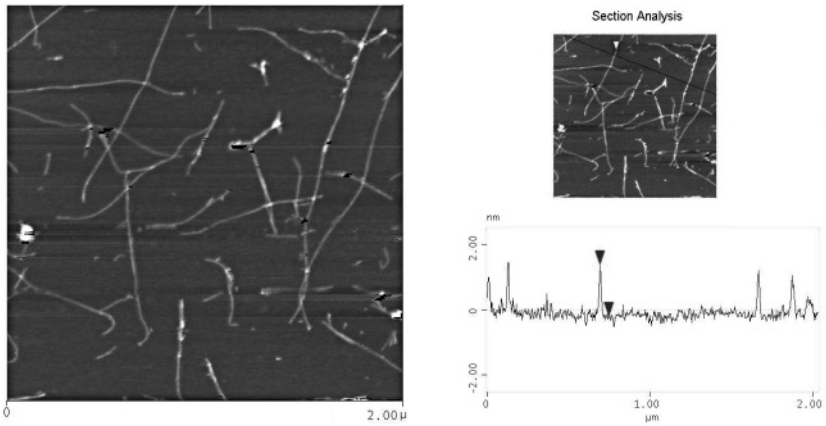


Figure 2. AFM analysis of **4b**. Left: Height data showing individualized, unbundled SWNTs. Right: Section analysis (along the black line) showing heights of a sample of SWNTs ranging from 1.2 to 1.6 nm, indicating that they were all unbundled.

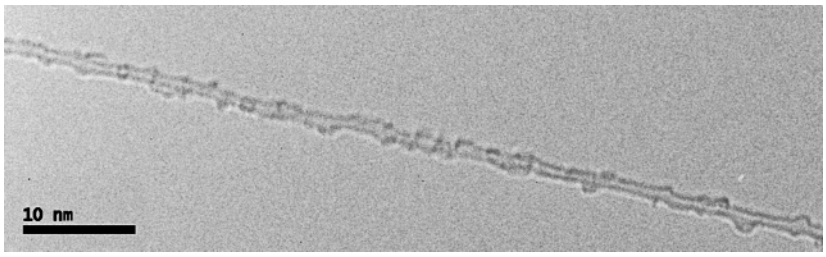


Figure 3. TEM of **4b**, SDS-free SWNTs deposited from suspension in $CHCl_3$.

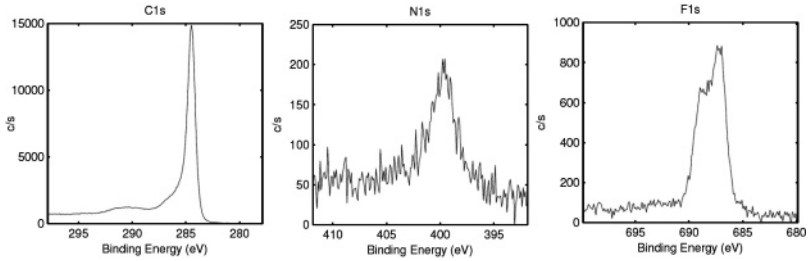


Figure 4. XPS analysis of **1b** functional SWNTs bearing arylfluoride moieties. The XPS pass energy was 26.00 eV with a 45° takeoff angle and a 100 μm beam size. The nitrogen present in the sample has been discussed previously and is attributed to possibly some aryldiazo moieties and N_2 surface contamination.[5]

the aryl moiety) from the total, an average of 1 functional group per 24 nanotube Cs is calculated. This data agrees closely with the data obtained from the TG analysis (Table 1) and shows the high degree of coverage expected from this triazene functionalization technique.

Conclusion

In summary, a protocol has been developed to synthesize stable triazenyl compounds, easily purified and characterized, that can be attached to SWNTs via proven diazonium chemistry. This protocol brings diversity to the SWNT functionalization field and addresses potential hazards of the synthesis and long-term storage of unstable diazonium salts. With use of stable triazenes, diazonium-based chemistry can be accessed via the in situ generation of diazonium species in water to achieve high degrees of functionalization in commonly used SWNT/SDS suspensions without the need to isolate, store, and characterize diazonium salts.

Experimental Section

General Methods. Solvents were distilled over calcium hydride under a nitrogen atmosphere. Anhydrous *N*,*N*-dimethylformamide was purchased from Alfa Aesar and stored under a dry nitrogen atmosphere over molecular sieves. All starting compounds were purchased from Sigma-Aldrich and used without further purification unless otherwise stated. SWNTs were obtained from the HiPco laboratory at Rice University and used without further purification. Aryltriazenes are known to have chemotheraputical properties and can be carcinogenic; they should be handled with appropriate care.[10] Silica gel plugs and flash chromatography were carried out on silica gel (230−400 mesh from EM science). For all triazene-containing compounds, the silica gel was made alkaline by treatment with a 20% solution of triethylamine in eluent, during slurry packing, prior to use. Thin-layer chromatography was carried out on glass plates coated with silica gel 60 F_{254} with a layer thickness of 0.25 mm purchased from EM Science which were washed with triethylamine prior to use. Proton chemical shifts (δ) are reported in ppm downfield from tetramethylsilane (TMS). Thermogravimetric analysis was performed from 26 to 850 °C at 10 °C/min under argon. Raman spectroscopy was performed on a Renishaw Ramascope using a 633 nm He−Ne laser. Mass spectrometry was done in the Rice University Mass Spectrometry Laboratory. XPS was carried out on a PHI Quantera SXM Scanning X-ray Microprobe with a pass energy of 26.00 eV, 45° takeoff angle, and a 100 μm beam size. Naming of compounds was carried out using Beilstein Autonom when possible.

4-Fluorophenyl (3,3-diethyl)triazene (1a). 4-Fluoroaniline (5.79 g, 52.0 mmol) was dissolved in dichloromethane (25 mL) in a dry 100 mL round-bottom flask equipped with a stir bar under an atmosphere of N_2. The reaction vessel was then placed in an ice bath and the solution was stirred. To the solution was then added $BF_3{\cdot}Et_2O$ (14.8 g, 104 mmol) via syringe, followed by slow addition of isoamyl nitrite over 5 min (12.2 g, 104 mmol). This mixture was stirred at 0 °C for 1 h during which time a solid formed in the flask. K_2CO_3 (21.6 g, 156 mmol) was added followed by syringe addition of diethylamine (11.4 g, 156 mmol) over 2 min. A mild exothermic reaction ensued and the solid dissolved. This mixture was stirred at room temperature for 1 h to ensure complete conversion to the triazene. The resultant mixture was diluted with dichloromethane and extracted with H_2O (50 mL) three times, the organic solution was concentrated in vacuo, and the residue was purified by column chromatography (alkaline silica gel, hexanes/CH_2Cl_2 = 3/1) to afford **1a** (9.95 g, 98%) as a red oil. IR (neat): 2976 (m), 1502−1090 (m) cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 7.38 (m, 2H), 6.97 (m, 2H), 3.61 (q, J = 7.2 Hz), 1.14 (t, J = 7.2 Hz). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 160.8 (d, J_{C-F} = 242.9 Hz), 147.9 (d, J_{C-F} = 2.8 Hz), 121.8 (d, J_{C-F} = 7.9 Hz), 115.3 (d, J_{C-F} = 22.3 Hz), 44.8 (br), 12.9 (br). HRMS calcd for $C_{10}H_{14}FN_3$ 195.1172, found 195.1174.

4-Fluorophenyl SWNT (1b). 4-Fluorophenyl (3,3-diethyl)-triazene, **1a** (0.547 g, 2.8 mmol), was added to an aqueous suspension[4] of SDS-wrapped SWNTs (200 mL, 40 mg/L, 0.7 mequiv of C) and subsequently a film formed on the water. The pH of the suspension was adjusted to 2 with 6 M HCl; the film disappeared after stirring for 5 min. After the organic layer dissolved, the pH of the suspension was adjusted to 10 with 6 M NaOH. The mixture was allowed to stir at room temperature for 1 h at which point it was poured into 300 mL of acetone, to remove the SDS micelle, and filtered over a 1 μm polycarbonate membrane. The resultant solid was suspended in dimethylformamide (DMF) and filtered over a 1 μm poly(tetrafluoroethylene) (PTFE) membrane. The solid was then washed with a copious amount of acetone and dried to yield **1b** (0.006 g). Raman D/G ratio 0.36; XPS atomic concentration C 95.38, N 1.44, F 3.18; TGA mass loss 22%.

[4-(2-Aminoethoxy)phenyl](3,3-diethyl)triazene (10). 9 (9.64 g, 26.3 mmol) was added to a 250 mL round-bottom flask. To this was added tetrahydrofuran (125 mL) and hydrazine monohydrate (4.21 g, 84.2 mmol). The reaction vessel was equipped with a condenser and allowed to stir at 66 °C for 12 h. After cooling, the precipitated phthalhydrazide was removed by filtration and the resultant supernatant was concentrated to afford **10** (5.83 g, 94%) as a light orange oil. IR (neat): 3362 (w), 2973 (w), 2933 (w), 2875 (w), 1718 (w), 1599 (w), 1499 (s), 1236 (s), 1100 (m), 1031 (w), 832 (w) cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 7.38 (d, J = 9.0 Hz, 2 H), 6.89 (d, J = 9.0 Hz, 2 H), 4.00 (t, J = 5.1 Hz, 2 H), 3.75 (q, J = 7.2 Hz, 4 H), 3.08 (t, J = 5.2 Hz), 1.77 (br s, 2 H), 1.27 (t, J = 7.2 Hz, 6 H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 156.7, 145.5, 121.5, 114.9, 69.8, 41.5.

Biotin [4-(2-Aminoethoxy)phenyl](3,3-diethyl)triazene Amide (11a). 10 (0.277 g, 1.2 mmol) was added to a 50 mL round-bottom

(10) Benigni, R. *Chem. Rev.* **2005**, *105*, 1767.

flask equipped with a stir bar; to this was added biotin *N*-hydroxysuccinimide ester[11] (0.400 g, 1.2 mmol). The flask was sealed and placed under an N_2 atmosphere. The solids were then dissolved in 25 mL of anhydrous DMF followed by addition of triethylamine (0.142 g, 1.4 mmol). The reaction mixture was allowed to stir at room temperature for 12 h at which point it was diluted with dichloromethane (200 mL) and washed with three portions of H_2O (150 mL). The resulting organic layer was dried over $MgSO_4$ and filtered, and the filtrate was concentrated under reduced pressure. The crude reaction material was purified by silica chromatography (alkaline silica gel, CH_2Cl_2/MeOH = 18/1) to afford **11a** (0.414 g, 75%). IR (neat): 3289 (s), 3080 (m), 2972 (m), 2930 (s), 2871 (m), 1701 (s), 1645 (s), 1553 (m), 1503 (m), 1461 (m), 1239 (s), 1094 (m), 912 (w), 834 (w), 731 (m) cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 7.35 (d, J = 9.0, 2 H), 7.01 (t, J = 5.6 Hz, 1 H), 6.86 (d, J = 9.0 Hz, 2 H), 6.82 (br s, 1 H), 5.89 (br s, 1 H), 4.39 (m, 1 H), 4.19 (m, 1 H), 4.04 (t, J = 5.1 Hz, 2 H), 3.72 (q, J = 7.2 Hz, 4 H), 3.63 (m, 2 H), 2.82 (m, 2 H), 2.63 (d, J = 12.8 Hz, 1 h), 2.22 (t, J = 7.5 Hz, 2 H), 1.65 (m, 4 H), 1.24 (m, 8 H). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 173.9, 164.5, 156.3, 145.7, 121.5, 114.9, 67.5, 61.8, 60.3, 55.9, 40.6, 39.2, 36.1, 28.4, 28.1, 25.8.

(11) Charvet N.; Reiss P.; Roget A.; Dupuis A.; Grünwald D.; Carayon S.; Chandezon F.; Livache T. *J. Mater. Chem.* **2004**, *14*, 2638.

Biotin [4-(2-Aminoethoxy)phenyl] Amide SWNT (11b). A procedure similar to the formation of **1b** using **11a** (0.369 g, 0.8 mmol), and an aqueous suspension of SWNTs (60 mL, 40 mg/L, 0.2 mequiv of C) was carried out to yield **11b** (0.008 g).

Acknowledgment. Financial support from the Defense Advanced Research Projects Agency, the Office of Naval Research, the Air Force Office of Scientific Research, and the National Aeronautics and Space Administration is gratefully acknowledged.

Supporting Information Available: Detailed syntheses of compounds **2a**−**6a**, **2b**−**6b**, and **7**−**9**. This material is available free of charge via the Internet at http://pubs.acs.org.

CM060020L