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Synthesis and Properties of a 1,3-Thiazole Extended *p*-Terphenoquinone. A New sp^2 Nitrogen Atom-Containing Terquinone Derivative

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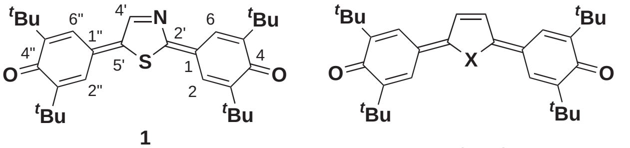
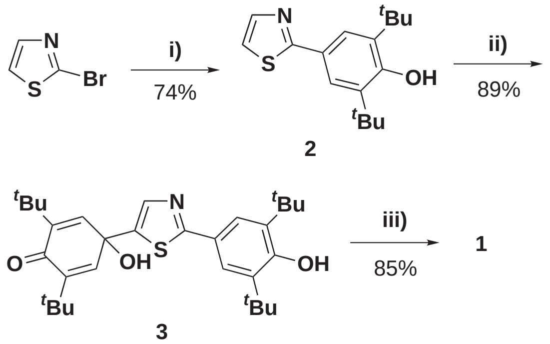
2,5-Bis(3,5-di-*tert*-butyl-4-oxo-2,5-cyclohexadien-1-ylidene)-2,5-dihydrothiazole, which is to our knowledge, the first *p*-terphenoquinone incorporating a 1,3-thiazole ring, had a sharp and strong absorption in the visible region and good electron affinity enhanced by sp^2 nitrogen atom. Alkali-metal reduction afforded the corresponding dianion, which showed strong fluorescence.



1

4: X = CH=CH
5: X = S
6: X = O

Chart 1. Thiazole-extended *p*-terphenoquinone **1** and other terquinones.



Scheme 1. Synthesis of **1**. Reagents and conditions: i) 3,5-di-*tert*-butyl-4-hydroxyphenylboronic acid, $Pd(PPh_3)_4$, K_2CO_3, DME, H_2O; reflux, 16 h; ii) 2.2 equiv of *n*-BuLi/ether, −78 °C, 1 h, then 2,6-di-*tert*-butylbenzoquinone; iii) excess anhyd. $CuSO_4$, toluene, reflux, 16 h.

Extended quinones have attracted considerable attention from the viewpoints of their structural, physicochemical, and especially, electrochemical properties.[1] In particular, *p*-quinones incorporating five-membered heteroaromatics have been extensively studied. Thiophene-, furan-, selenole-, tellurophene-, and *N*-methylpyrrole-incorporated *p*-terpheno- and/or quaterphenoquinone derivatives have been synthesized. They exhibit amphoteric redox properties as well as potentials for use as novel dyestuffs and in photoelectronic devices.[2–6] Although the synthesis of oxadiazole- and thiadiazole-inserted derivatives has been reported in a Japanese patent,[7] derivatives extended with a 1,3-thiazole ring have remained unknown.[8] The electron-withdrawing 1,3-thiazole ring should increase the acceptor ability of the quinones, while the nitrogen atom should act as a functional part for intermolecular interactions, such as the formation of metal complexes and supramolecules having hydrogen bonds. Furthermore, thiazole-containing π-systems have been investigated as n-type organic field-effect transistors.[9] In this context, we designed a new *p*-terphenoquinone derivative containing a 1,3-thiazole ring, 2,5-bis(3,5-di-*tert*-butyl-4-oxo-2,5-cyclohexadien-1-ylidene)-2,5-dihydrothiazole (**1**), and here report its facile synthesis and fundamental properties (Chart 1).

Synthesis of **1** is outlined in Scheme 1. It is thought that 2-(3,5-di-*tert*-butyl-4-hydroxyphenyl)thiazole (**2**) is a key intermediate, because **2** is not only the precursor for **1** but also for other quinonoid compounds containing a thiazole unit. Two-step synthesis of **2** has been reported in a U.S. Patent;[10] however, we thought that Suzuki–Miyaura coupling would be a better method. Pd^0-catalyzed cross-coupling of 2-bromothiazole and 3,5-di-*tert*-butyl-4-hydoxyphenylboronic acid afforded **2** in 74% yield. Then, we tried to introduce one more phenol ring to **2** via bromination and Suzuki–Miyaura coupling. Bromination of the thiazole ring, however, did not occur probably because of a competitive electron-transfer reaction. We, thus, applied a lithiation-functionalization protocol. Dilithiation of **2** was carried out by treatment with two equivalents of butyllithium in THF at −78 °C, and the dilithio compound reacted with 2,6-di-*tert*-butylbenzoquinone to give **3** in 89% yield. Initially, we planned to reduce **3** to the corresponding bis-phenol, but found that **3** underwent dehydration to form quinone **1**. The NMR sample of **3** in $CDCl_3$ turned purple after several days, and the signals of **1** were observed in its spectrum, probably because of contamination of the solvent by small amount of acid. Dehydration of **3**, therefore, was carried out by treatment with anhydrous $CuSO_4$ in toluene,[11] and **1** was obtained in 85% yield.

Terquinone **1** was isolated green needles with golden metallic luster and was deep purple in solution, with good air and thermal stability. Well-resolved signals were observed in ^1H and ^{13}C NMR spectra, indicating negligible contribution of diradical character on **1** (Table 1). The proton on the thiazole ring (H4′) was observed at a significantly low magnetic field (δ 8.76), which is caused by the electron-withdrawing effect of the adjacent sp^2-nitrogen atom as well as the two quinone methide units. Among the non-equivalent four protons of six-membered rings, H6 was shifted remarkably downfield (δ 8.07) compared to the other three protons, probably because of the anisotropic effect of the nitrogen atom. ^{13}C chemical

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Table 1. Selected ^1H and ^{13}C NMR Spectral Data[a)] of **1**

	Position					
	2	6	4′	2″	6″	4 and 4″
^1H[b)]	7.25[d)]	8.07[d)]	8.76	7.15[d)]	7.51[d)]	
^{13}C[c)]	127.67	126.70	156.74	129.78	124.80	186.39 185.82

a) In $CDCl_3$. The chemical shift assignment was determined by COSY, NOESY, HMQC, and HMBC techniques. b) δ/ppm in 600 MHz. c) δ/ppm in 150 MHz. d) Doublet, $J = 2.5$ Hz.

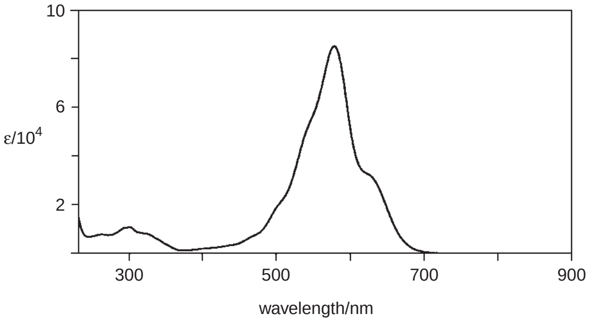


Fig. 1. UV–vis spectrum of **1** in CH_2Cl_2.

Table 2. Redox Potentials[a)] of **1** and **5**

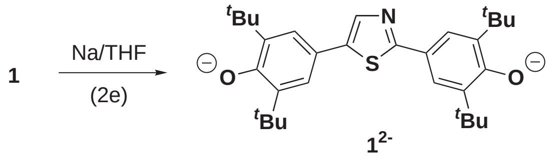
	E_2^{ox}	E_1^{ox}	E_1^{red}	E_2^{red}
1	+1.68[b)]	+1.38[b)]	−0.44	−0.65
5		+1.03	−0.63	−0.79

a) In CH_2Cl_2. b) V vs. Ag/Ag^+ in 0.1 M n-Bu_4NClO_4/CH_2Cl_2 at rt, scan rate 100 mV s^{-1}, ferrocene = +0.41 V. c) Peak potential.

shifts of carbonyl carbons (C4 and C4″) were comparable to those of the benzoquinonoid,[12] thienoquinonoid,[2] and furoquinonoid[4] isomers (**4**, **5**, and **6** in Chart 1: δ 186.06, 185.81, and 185.72, respectively). Two pinch bonds of **1**, C1–C2′ and C5′–C1″, can easily rotate; their rotational barriers ($\Delta G^{\ddagger}$) were estimated to be 85.4 ± 0.8 and 78.7 ± 0.8 kJ mol^{-1} respectively, by the measurement of the coalescence phenomena among signals of the *tert*-butyl protons.

UV–vis spectrum of **1** is shown in Fig. 1. A sharp and strong absorption was observed at $\lambda_{max}(CH_2Cl_2) = 578$ nm, which is consistent with those of **4**, **5**, and **6**. The absorption end extends to the near-infrared region (700 nm). The longest absorption maxima of **1** showed a slight bathochromic shift as compared to that of **5** ($\lambda_{max}(CH_2Cl_2) = 568$ nm).[13]

Electrochemical properties of **1** were studied using cyclic voltammetry. For comparison, the redox potentials of **5** were measured under the same conditions, and the data are summarized in Table 2. Compound **1** showed two sets of reversible reduction waves, of which the first and second reduction potentials were more positive than those of **5**. This indicates that introducing an electron-withdrawing 1,3-thiazole unit to a quinone skeleton is an effective way of increasing its electron affinity. Whereas **5** showed a reversible oxidation wave at a relatively low potential, **1** showed two oxidation peaks and both of them were irreversible.



Scheme 2. Alkali-metal reduction of **1**.

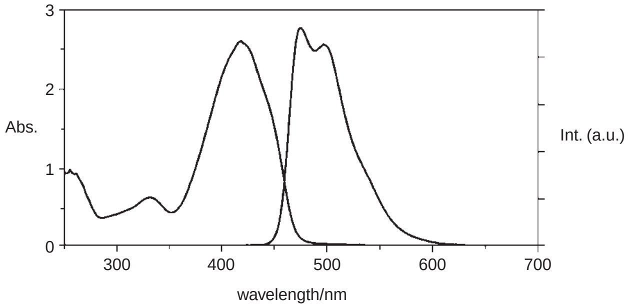


Fig. 2. UV–vis and emission spectra of dianion $\mathbf{1}^{2-}$ in THF.

Alkali-metal reduction was performed for the generation of the dianion of **1**. In a degassed THF solution, **1** was reduced by using with a sodium mirror. The reaction was monitored by the change in UV–vis spectra. As the reaction proceeds, the absorption of **1** gradually decreased and a new absorption at 350–450 nm appeared, thus indicating the formation of dianion $\mathbf{1}^{2-}$ by electronic reduction (Scheme 2). The solution color changed from deep purple to yellow. The final UV–vis spectrum is shown in Fig. 2 ($\lambda_{max} = 419$ and 332 nm). Interestingly, the solution of $\mathbf{1}^{2-}$ exhibited strong fluorescence. The emission spectrum is also shown in Fig. 2, and the first and second emission maxima were 475 and 497 nm, respectively.[14]

In conclusion, a new p-terphenoquinone extended with a 1,3-thiazole ring **1** was synthesized in three steps from 2-bromothiazole. Facile di-lithiation of the key intermediate **2** should be a useful synthetic tool for a variety of novel thiazole-containing quinonoid compounds. Terquinone **1** showed a sharp and strong absorption in the visible region, considerably low reduction potentials in the cyclic voltammetry, and strong fluorescence in the dianion state, which indicates that **1** has the potential for use in functionalized organic materials.

Experimental

Melting points were measured on a Yanaco MP 500D apparatus and were uncorrected. Mass spectra were recorded with a JEOL SX-102 instrument by EI or FAB method. Infrared spectra were recorded on a Perkin-Elmer 1650 FT-IR spectrophotometer in KBr disks and only significant absorption bands are reported. UV–vis absorption spectra were obtained on a Jasco V-570 spectrophotometer. ^1H and ^{13}C NMR spectra were measured on Varian UNITY plus 600 (600 MHz), JEOL GSX-400 (400 MHz), or JEOL EX-270 (270 MHz) instrument, and recorded in δ value with tetramethylsilane as an internal standard. Cyclic voltammetry was performed on a BAS CV-50W voltammetric analyzer. Microanalyses were performed at the Elemental Analysis Center, Faculty of Science, Osaka University.

2-(3,5-Di-*tert*-butyl-4-hydroxyphenyl)thiazole (2). 3,5-Di-*tert*-butyl-4-hydoxyphenylboronic acid (500 mg, 2.0 mmol), sodium carbonate (1.27 g, 12 mmol), and water (4 mL) were added to a solution of 2-bromothiazole (274 mg, 1.7 mmol) and $Pd(PPh_3)_4$ (115 mg, 0.1

mmol) in 1,2-dimethoxyethane (10 mL) under nitrogen atmosphere. The mixture was heated at reflux for 16 h. After cooling to room temperature, the mixture was quenched with 1 M (=1 mol L^{-1}) HCl (10 mL) and extracted with diethyl ether (20 mL × 3). The combined organic phase was washed with water and brine and dried with anhydrous Na_2SO_4. After evaporation of solvent in vacuo, the residue was purified by column chromatography (SiO_2, 50 g, eluent; 10% ethyl acetate/hexane) to give **2** (357 mg, 74%): colorless plates (benzene/hexane); mp 127–128 °C; MS(EI) m/z 289 (M^+, 100%), 274 [$(M - CH_3)^+$, 90%]; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80 (d, $J = 3.3$ Hz, 1H), 7.78 (s, 2H), 7.22 (d, $J = 3.3$ Hz, 1H), 5.46 (s, 1H), 1.50 (s, 18H); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 169.67, 155.76, 143.31, 136.52, 125.39, 123.81, 117.50, 34.42, 30.21; IR (KBr) ν/cm^{-1} 3584s (OH), 2956s, 1434s, 1388s, 1237s, 1118m, 921m, 880m, 849s, 811w, 769w, 704w, 604m, 546w, 512w; Found: C, 70.49; H, 8.07; N, 4.87%. Calcd for $C_{17}H_{23}NOS$: C, 70.55; H, 8.01; N, 4.84%.

2-(3,5-Di-*tert*-butyl-4-hydroxyphenyl)-5-(3,5-di-*tert*-butyl-1-hydroxy-4-oxo-2,5-cyclohexadienyl)thiazole (3). A 1.6 M solution of butyllithium in hexane (1.5 mL, 2.4 mmol) was added dropwise to a solution of **2** (287 mg, 1.0 mmol) in THF (7.5 mL) at −78 °C. After stirring at −78 °C for 1 h, a solution of 2,6-di-*tert*-butylbenzoquinone (242 mg, 1.1 mmol) in THF (5 mL) was added, and then the mixture was stirred at 0 °C for 1.5 h. After hydrolysis with saturated ammonium chloride aqueous solution, the mixture was extracted with ethyl acetate (20 mL × 3), washed with water and brine, and dried with Na_2SO_4. The solvent was evaporated in vacuo, and the residue was washed with hexane to give 2-(3,5-di-*tert*-butyl-4-hydroxyphenyl)-5-(3,5-di-*tert*-butyl-1-hydroxy-4-oxo-2,5-cyclohexadienyl)thiazole (455 mg, 89%). This compound was used for the next reaction without further purification; colorless powder; mp > 150 °C (decomp.); ^{1}H NMR (270 MHz, $CDCl_3$) δ 7.72 (s, 2H), 7.55 (s, 1H), 6.71 (s, 2H), 5.48 (s, 1H), 1.93 (brs, 1H), 1.48 (s, 18H), 1.24 (s, 18H); ^{13}C NMR (67.8 MHz, $CDCl_3$) δ 185.70, 170.19, 156.08, 145.97, 140.43, 140.00, 139.50, 136.59, 125.12, 123.70, 68.49, 34.84, 34.43, 30.20, 29.36; HRMS Found: m/z 509.2968. Calcd for $C_{31}H_{43}NO_3S$: [M^+], 509.2964.

2,5-Bis(3,5-di-*tert*-butyl-4-oxo-2,5-cyclohexadien-1-ylidene)-2,5-dihydrothiazole (1). Compound **3** (50 mg, 0.1 mmol) was added to a suspension of well-dried anhydrous $CuSO_4$ (500 mg, 3.1 mmol) in toluene (10 mL) under a nitrogen atmosphere. The mixture was then refluxed for 16 h. After removal of inorganic materials by filtration, the filtrate was evaporated in vacuo, and the residue was purified by column chromatography (SiO_2, 20 g, eluent; 10% ethyl acetate/hexane) to give **1** (42 mg, 85%): metallic green needles (benzene–hexane); mp 248–249 °C (decomp.) MS (FAB) m/z 494.4 [$(M + H)^+$]; ^{1}H NMR (600 MHz, $CDCl_3$) δ 8.76 (s, 1H), 8.07 (d, $J = 2.5$ Hz, 1H), 7.51 (d, $J = 2.5$ Hz, 1H), 7.25 (d, $J = 2.5$ Hz, 1H), 7.15 (d, $J = 2.5$ Hz, 1H), 1.38 (s, 9H), 1.37 (s, 27H); ^{13}C NMR (150 MHz, $CDCl_3$) δ 186.39, 185.82, 163.48, 156.74, 152.56, 151.62, 148.73, 148.58, 148.44, 129.78, 128.86, 128.46, 127.67, 126.70, 124.80, 36.13, 36.02, 35.81, 35.79, 29.74, 29.67, 29.64, 28.60; UV–vis. (CH_2Cl_2) λ_{max}/nm (log ε) 627 (4.51), 578 (4.93), 540sh (4.70), 500sh (4.27), 327 (3.89), 262 (3.88), IR (KBr) ν/cm^{-1} 2956m, 1590s(CO), 1454w, 1387w, 1361m, 1331w, 1253w, 1126m, 1086w, 1033w, 884w, 859m, 816w, 716w; Found: C, 75.50; H, 8.45; N, 2.84%. Calcd for $C_{31}H_{41}NO_2S$: C, 75.72; H, 8.40; N, 2.85%.

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13 Compound **5** was prepared and UV–vis spectrum was measured under the same condition as **1**.

14 The quantum yield could not obtain because the determination of the solution concentration and the reduction conversion was difficult.