

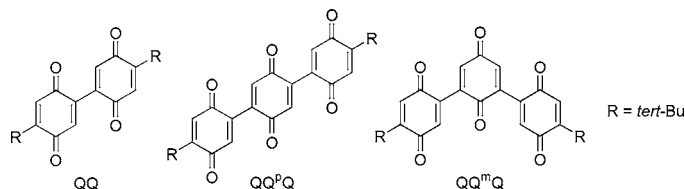
Synthesis, Structure, and Properties of Benzoquinone Dimer and Trimers Bearing *t*-Bu Substituents

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ABSTRACT



Highly soluble and stable quinone dimer and trimers were successfully yielded by introduction of *t*-Bu substituents. In X-ray structure analysis, the dimer quinone moiety was distorted into the boat shape, which was clarified by MO calculations. X-ray and UV/vis studies indicated that the covalently linked quinone moieties bear a large torsional angle. Nevertheless, the reduction potentials rose significantly with the order of monomer < dimer < trimer, indicating that the negative charge was efficiently delocalized within the radical anions.

Benzoquinone, or quinone, is abundant in chemistry.¹ In biological sciences, it constitutes part of the structure of ubiquinone² (coenzyme Q), which acts as a lipid-soluble electron carrier in the membrane-bound respiratory chain. Quinone is also employed as an electron-acceptor moiety in photoinduced electron transfer (PIET) in (artificial) photosynthesis.³ The strong electron-acceptor character of quinone plays an important role in these systems. The radical anion state is stabilized by delocalization of the negative charge in linked quinone derivatives (i.e., quinone oligomers), thus acceptor ability is likely to increase significantly in quinone oligomer systems. In relation to this, conocurvone is a natural compound bearing quinone moieties. It is comprised of three covalently linked naphthoquinones, and has attracted much

attention because of its anti-HIV activities.⁴ In addition, humic acid contains a mixture of quinone oligomers.⁵

Nevertheless, only a few quinone oligomers are reported,⁶ and even the quinone dimer has yet to be fully characterized. This may be due to their poor solubility, since unsubstituted quinone dimers and trimers are reported to be sparingly soluble in common organic solvents.^{5a} Moreover, they are so unstable that they decompose gradually when recrystallized from ethanol. In this report, we have presented the design, synthesis, structural and electrochemical properties,

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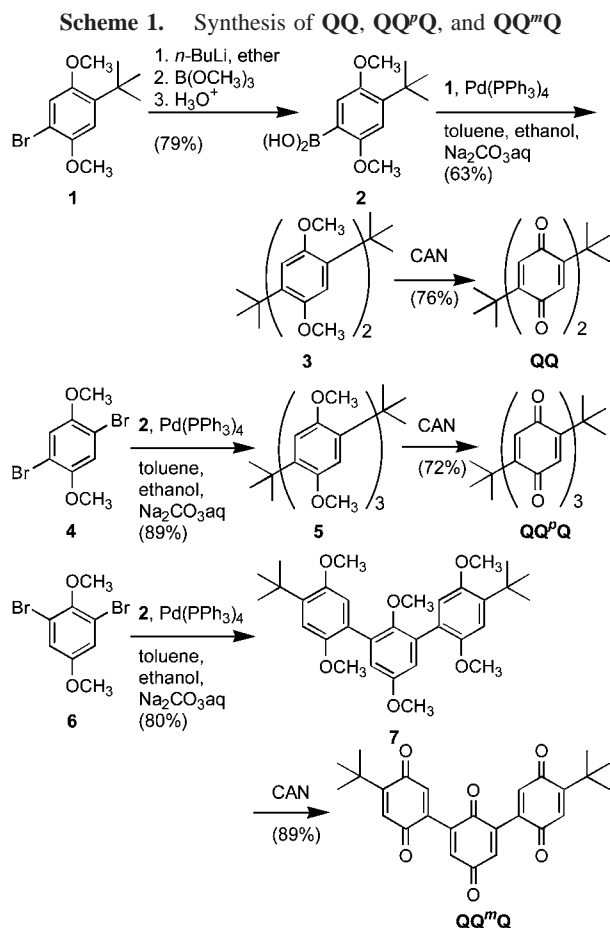
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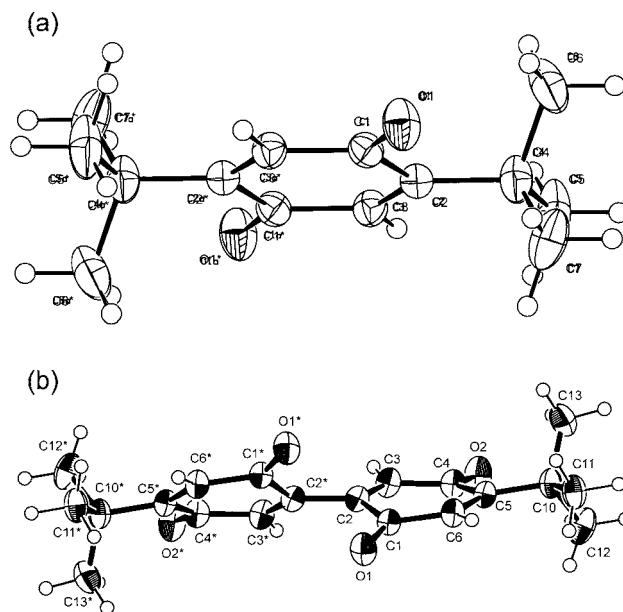
and acceptor characteristics of quinone dimer and trimer derivatives. Furthermore, we have reported that quinone dimer (**QQ**)⁷ and trimers (**QQ^pQ** and **QQ^mQ**) can be easily handled by the introduction of *t*-Bu groups.

QQ, **QQ^pQ**, and **QQ^mQ** were synthesized as shown in Scheme 1. 2-Bromo-5-*tert*-butyl-1,4-dimethoxybenzene (**1**)



was converted to boronic acid **2**, then subject to Suzuki–Miyaura coupling⁸ with **1** to obtain the dimethoxybenzene dimer **3**. The dimer was oxidized by cerium ammonium nitrite (CAN) to afford **QQ** in good yield. Similarly, **QQ^pQ** was synthesized from 2,5-dibromo-1,4-dimethoxybenzene **4** via dimethoxybenzene trimers **5**, and **QQ^mQ** from 2,6-dibromo-1,4-dimethoxybenzene **6** via **7**. Owing to the *t*-Bu substituent, **QQ** was highly soluble in various organic solvents such as benzene, chloroform, ether, ethanol, and ethyl acetate, and moderately so in hexane. On the other hand, solubility was somewhat lower for **QQ^pQ** and **QQ^mQ**. In contrast with nonsubstituted quinone oligomers, none of the oligomers in this study underwent decomposition for at least several days when kept in the dark.

X-ray analysis of 2,5-*tert*-butyl-1,4-benzoquinone (**Q**) was performed for comparison. As shown in Figure 1a, the



Evidently, the boat formation of **QQ** should not be attributed to the *t*-Bu substituent, since the quinone ring of **Q** was not distorted (Figure 1a). Detailed examination of the X-ray structure of **QQ** revealed short intramolecular contact between the oxygen atoms (O1 and O1'), with an interatomic distance of 2.912(3) Å. This is considerably smaller than the sum of van der Waals radii of two oxygen atoms (3.04 Å),¹² and thus can be deemed responsible for the distortion. The short contact between the oxygen atoms may simply be attributed to packing demand. However, to investigate other factors, MO calculations were performed at the B3LYP/6-311+G(d,p) and HF/6-31G(d) levels. The former method was applied to obtain the optimized geometry of syn and anti conformers of the unsubstituted quinone dimer (**QQ'**) as a model compound. The quinone moiety was essentially planar and ϕ was found to be 137.1° in the optimized anti conformer. Conversely the boat-shaped quinone was reproduced in the syn conformer (ϕ was fixed at 37.7° based on the X-ray structure), where the oxygen–oxygen distance was 2.93 Å. It was noted that, at 1.07 kcal mol^{−1}, the energy difference was rather small, despite the large distortion observed in the syn conformer. This result, and the fact that distortion of the quinone ring into a boat shape is also observed in the naphthoquinone dimer,¹⁰ may indicate that the quinone ring substituted by a quinone moiety is considerably prone to distortion.

On the other hand, an HF/6-31G(d) calculation was used to estimate the rotational barrier of **QQ'**, where ϕ was varied between 0° (coplanar cis), 45°, 90°, 135°, and 180° (coplanar trans). It is recognized as difficult to accurately reproduce the experimental data of biaryl rotational barriers by MO methods.¹³ Nevertheless, this method was used, as it was considered worthwhile to obtain a comparison of results by identical calculation methods. The energy differences found

Table 1. Energy Differences (E_ϕ , in kcal mol^{−1}) for **QQ'**, FBP, and CIBP at Dihedral Angles ϕ of 0°, 45°, 90°, 135°, and 180°, Relative to the Energy at the Optimal Dihedral Angle ϕ_{opt} , Given at the Bottom^a

ϕ	QQ'	FBP ^b	CIBP ^b
0	10.49	12.64	46.46
45	0.76	0.90	9.75
90	1.28	1.03	0.00
135	1.48	0.31	4.64
180	4.83	6.12	22.74
ϕ_{opt}	62.16/134.95	57.13/128.82	89.66

^a HF/6-31G(d) calculation. ^b Reference 13.

are shown in Table 1, accompanied by values obtained previously for 2,2'-difluorobiphenyl (FBP) and 2,2'-dichlo-

robiphenyl (CIBP). The energy differences of **QQ'** were even smaller than the corresponding ones of CIBP, and were similar to those of FBP. This was probably due to differences in their van der Waals radii (F, 1.47 Å; O, 1.52 Å; Cl, 1.75 Å)¹² and covalent bond lengths (C–F, 1.34 Å; C=O, 1.21 Å; C–Cl, 1.73 Å). **QQ'** has two energy minima at 62° and 135°. Double energy minima were also seen in FBP (57° and 129°), while CIBP had only one energy minimum (90°). It is noteworthy that, in comparison of the energy minima of **QQ'**, E_{62° (syn conformer) is lower than E_{135° (anti conformer) by 1.48 kcal mol^{−1}. A preference for the syn conformer was found via MO calculations, as well as in electron diffraction studies of FBP and CIBP. This suggested the existence of a particular interaction between the halogen atoms. Similarly, this result implies that an oxygen–oxygen interaction may well exist in the quinone dimer, which may have been responsible for the syn conformation found in X-ray structure analysis of **QQ**. The presence of an oxygen–oxygen interaction was also supported by the result of the B3LYP/6-311+G(d,p) calculation. Despite the short contact between oxygen atoms and the distortion of the quinone moiety, the energetic disadvantage of the syn conformer was unexpectedly small. Conclusively, the boat shape observed in the X-ray crystal of **QQ** must have been due to the short contact between the adjacent oxygen atoms, which probably arose from the packing demand, and/or plausible oxygen–oxygen interaction. Although it was anticipated that X-ray analysis of **QQ''Q** and **QQ'''Q** would give further information on this issue, good **QQ''Q** and **QQ'''Q** crystals were not obtained, despite our best efforts.

Electronic absorption spectra (1,4-dioxane) of **Q**, **QQ**, **QQ''Q**, and **QQ'''Q** are shown in Figure 2. When the number

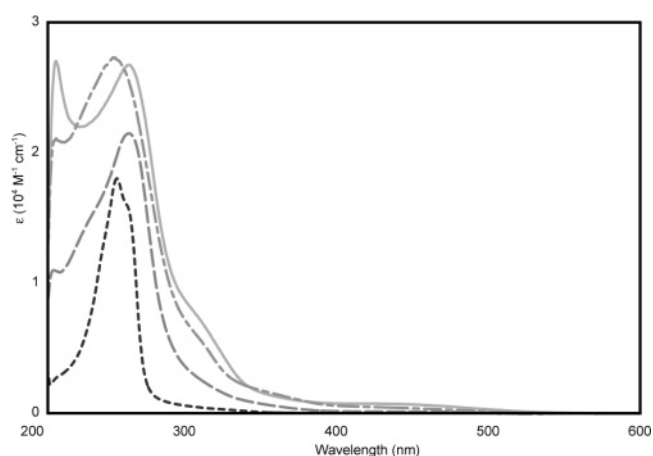


Figure 2. Electronic absorption spectra of **Q** (dotted), **QQ** (broken), **QQ''Q** (dash-dotted), and **QQ'''Q** (solid) in 1,4-dioxane.

of quinone moieties increased, molar absorption coefficients (ϵ) also increased, although wavelengths of maximum

(11) As seen in the X-ray structure of polymorphs of substituted bipyrrrole, the bond length linking two π moieties is sensitively altered depending on the dihedral angle: the pyrrole–pyrrole bond length of the anti conformer, where the dihedral angle $\phi = 180^\circ$, is 1.4362(17) Å, whereas that of the syn conformer, where $\phi = 40^\circ$, is 1.4490(16) Å (Merz, A.; Kronberger, J.; Dunsch, L.; Neudeck, A.; Petr, A.; Parkanyi, L. *Angew. Chem., Int. Ed.* **1999**, *38*, 1442).

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absorption (λ_{max} , π - π^* transition) were observed at almost the same position (ca. 260 nm). On the other hand, a new absorption band (shoulder) appeared around 300–340 nm in **QQ**, **QQ^pQ**, and **QQ^mQ**, indicating essential expansion of π conjugation over the adjacent moieties. In addition, a bathochromic shift of the absorption edge (n - π^* transition) was seen on chain elongation. As the energy level of the n orbital probably does not undergo substituent effects, this may suggest lowering of the LUMO level (π^* orbital).

The redox behaviors of **Q**, **QQ**, **QQ^pQ**, and **QQ^mQ** were measured by cyclic voltammetry (Table 2). In DMF solution,

Table 2. Reduction Potentials for Compounds **Q**, **QQ**, **QQ^pQ**, and **QQ^mQ**^a

compd	$E_1^{1/2}$	$E_2^{1/2}$	$E_3^{1/2}$	$E_4^{1/2}$	E_5^{pc}
Q	−1.05 (1e)	−2.13(1e)			
QQ	−0.78 (1e)	−1.25(1e)	−2.21 ^b		
QQ^pQ	−0.59 (1e)	−0.97(1e)	−1.31(1e)	−1.74 ^b	−2.28
QQ^mQ	−0.59 (1e)	−0.97(1e)	−1.32(1e)	−2.16(1e)	

^a Electrode: Pt (working), Pt (counter), and Ag/Ag⁺ (reference). Supporting electrolyte: *n*-Bu₄NClO₄. Solvent: DMF. Scan rate: 100 mV/s.
^b Irreversible (thus, E_x^{pc} is shown).

Q exhibited two well-defined one-electron reversible redox waves, corresponding to the formation of a radical anion, followed by dianion at higher potential. **QQ** showed three waves; the first and second ones were reversible corresponding to the formation of a radical anion and dianion, respectively, whereas the third was irreversible. The first, second, and third redox waves were reversible both for **QQ^pQ** and **QQ^mQ**; in contrast, the fourth and fifth redox waves were irreversible for **QQ^pQ**, while the fourth redox wave was also reversible for **QQ^mQ**. The initial reduction potentials were raised considerably in the order of monomer, dimer, and trimer. This indicates that radical anions generated from the dimer and trimers were stabilized by means of delocalization of the negative charge. It may be noteworthy

that almost identical $E_1^{1/2}$, $E_2^{1/2}$, and $E_3^{1/2}$ were observed in **QQ^mQ** and **QQ^pQ**. It had been expected that due to the strong electron-withdrawing substituent effect of the quinone moiety, the positions of substituents would affect the reduction potentials, as observed in different stability of 2,6-dinitrophenoxide compared with 2,5-dinitrophenoxide.¹⁴ Very little effect of the positions of substituents on E_1^{red} was also seen in comparison to 2,6-dichloro-*p*-benzoquinone (−0.23 V) and 2,5-dichloro-*p*-benzoquinone (−0.22 V).¹⁵

In conclusion, we have obtained quinone dimer (**QQ**) and trimers (**QQ^mQ** and **QQ^pQ**) in high yield, and found them to be highly soluble and stable due to *t*-Bu substituents. MO calculations showed the structural flexibility of **QQ**, and indeed X-ray analysis revealed distortion of the quinone moiety into the boat form. The origin of the distortion was due to the short contact between adjacent oxygen atoms, which arose from packing demand, an oxygen–oxygen interaction, or both. The first reduction potential was substantially lowered by covalent linkage of the quinone moieties. Regardless of the different molecular structure, the reduction potentials of **QQ^mQ** and **QQ^pQ** were found to be essentially identical. Studies on higher quinone oligomers ($n \geq 4$) and oligomers bearing an appropriate spacer are currently underway.

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Supporting Information Available: Synthetic procedures, spectroscopic data for compounds **QQ**, **QQ^pQ**, **QQ^mQ**, **2**, **3**, **5**, and **7**, and crystallographic data for **Q** and **QQ** (CIF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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