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Synthesis of *para*- or *ortho*-Substituted Triarylbilindiones and Tetraarylbiladienones by Coupled Oxidation of Tetraarylporphyrins

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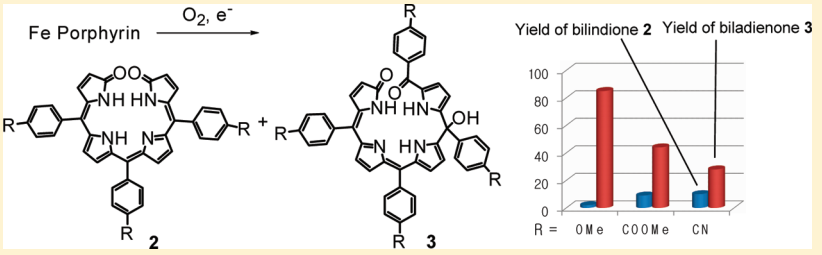
Supporting Information

ABSTRACT:



Coupled oxidation of [tetraarylporphyrinato]iron(III) chloride carrying substituents in the *ortho* or *para* positions was performed by allowing the iron porphyrin to react with dioxygen, ascorbic acid, and pyridine to give biladienone as the major product and bilindione as a minor one. Efforts to find reaction conditions and workup procedures to obtain bilindione improved the yields of triarylbilindiones ranging between 2% and 19%. Electron-withdrawing substituents in the *para* position on the aryl groups increased the selectivity of bilindione relative to biladienone: the isolated yields of bilindione and biladienone were 2% and 85% (OMe), 6% and 44% (COOMe), and 7% and 28% (CN), respectively. Electronic effects of substituents affected both isolation procedures and the spectroscopic properties of bilindiones. Tri(4-methoxyphenyl)bilindione showed a red-shifted electronic absorption compared to unsubstituted and 4-methoxycarbonyl substituted analogues. This was ascribed to the destabilization of the HOMO−1 level by the methoxy groups.

INTRODUCTION

Bilindiones[1] are important compounds as the prosthetic group of photoreceptor proteins[2] and an intermediate of heme degradation.[3] Natural bilindiones have substituents in the pyrrole β-positions. In nature, bilindiones are synthesized from iron porphyrin in the sequence of reactions catalyzed by heme oxygenase.[3] As an analogous reaction, coupled oxidation of iron porphyrins with substituents at the pyrrole β-positions was studied in detail by Lemberg and others.[4] The reaction attracts interest due to similarity to the heme oxygenase catalyzed reactions.[5] Coupled oxidation can be used to prepare bilindiones, particularly symmetrically substituted ones. However, to prepare unsymmetrically substituted bilindiones in the laboratory, multistep synthesis is needed to control regiochemistry.[6]

On the other hand, bilindiones carrying substituents in the bridging methine carbons (*meso* carbon) have not been found in nature. A number of porphyrin derivatives carrying *meso* substituents have been reported since the preparation of *meso*-substituted porphyrins is straightforward.[7] Oxidation of *meso*-substituted porphyrins has been investigated using various reagents such as thallium or cerium salts,[8] N_2O_4,[9] $NaNO_2$−TFA−air,[10] $I_2/AgClO_4$,[11] *m*-CPBA,[12] or photochemically generated singlet oxygen.[13] These oxidation reactions gave biladienones or substituted cyclic tetrapyrroles, and formation of bilindiones has not been reported. Tetraarylbiladienone is in equilibrium with the dehydrated tetraarylbilatrienone under acidic conditions.[14] Smith and co-workers reported that dodecasubstituted porphyrin with nonyl groups on the phenyl groups, upon chemical oxidation gave tetraarylbilatrienone, which is resistant to hydration.[15] Recently, Lente and Fabian[16] reported kinetic studies of the oxidation of Fe(III)TPPS with H_2O_2 and HSO_5^-, and mass spectroscopic analysis of the products showed that the iron complex of bilindione was formed.

Photochemical *Z*-*E* isomerization is the key reaction of bilindione as the prosthetic group of phytochrome.[2b,17] In addition to *Z*-*E* isomerization, bilindione has dynamic helical chirality and has enantiomers owing to the framework chirality.[18] Chiral framework of bilindione was used to construct chiral relay systems[19] and used as a chiral dopant for liquid crystals.[20] The coordinating ability of bilindione to metals is also interesting,[21] although only the iron complex of triarylbilindione has been reported.[16] Bilindiones with aryl groups could be employed as a key component in materials science such as an active layer of electronic devices, because a variety of substituents could be introduced to the aryl groups to modify the molecular orbital

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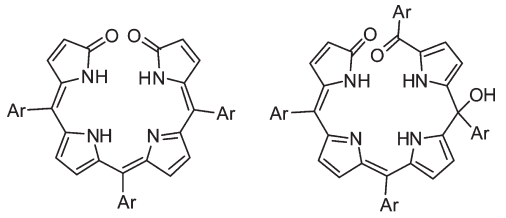
Scheme 1. Structures of Triarylbilindione and Tetraarylbiladienone



energies as well as crystal packing properties.[22] Bilindiones with *ortho*-substituted aryl groups could be attractive candidates for a scaffold for artificial receptors where the *ortho* substituents could serve as a recognition functional group.[23] The substituents in the *ortho* positions could form an array of recognition groups in a convergent fashion to construct a multipoint binding pocket.[23] Since a variety of tetraarylporphyrins have been prepared so far, coupled oxidation of tetraarylporphyrins substituted in either the *ortho*, *meta*, or *para* positions should be a versatile route to this class of compounds.

We reported that coupled oxidation of [5,10,15,20-tetraarylporphyrinato]iron(III) chloride at room temperature gave biladienone,[24] whereas oxidation under reflux conditions gave both biladienone and bilindione (Scheme 1).[25] Although degradation of iron tetraarylporphyrin in the presence of O_2 was reported in the literature,[26] detailed investigation on the structures of degraded products of tetraarylporphyrin was not reported to our knowledge. In this paper we addressed two unresolved issues, that is, (1) conversion of a series of tetraarylporphyrins having substituents in the *para* positions to bilindiones by coupled oxidation to investigate electronic effects of the substituents on the reaction selectivity and the properties of the resulting bilindiones, and (2) coupled oxidation of an *ortho*-substituted tetraphenyporphyrin. First, we describe the procedure of coupled oxidation of *para*-substituted tetraphenylporphyrin to obtain *para*-substituted triarylbilindiones. We found that electron-withdrawing groups on the aryl groups improved the yield of bilindione, whereas electron-donating groups improved the yield of biladienone. Electronic effects of substituents of the phenyl rings on the electronic energy of bilindiones were examined by use of molecular orbital calculations and UV−vis spectroscopy. We also attempted to cleave tetra(*o*-methoxyphenyl)porphyrin and we obtained both biladienone and bilindione carrying *ortho* substituents in a fair to good yield.

RESULTS AND DISCUSSION

Bilindione Synthesis from [Tetraarylporphyrinato]iron(III) Chloride. In preliminary studies, we found that [5,10,15,20-tetraphenylporphyrinato]iron(III) (FeTPP, **1f**) can undergo oxidative cleavage at room temperature to yield a linear tetrapyrrole, biladienone **3f**, in the presence of O_2, ascorbic acid, and pyridine in chloroform.[25] We also reported that heating the reaction mixture under reflux afforded the further oxidized linear tetrapyrrole, bilindione **2f**, as a minor product. Under reflux conditions, both (*Z*,*Z*,*Z*)-bilindione and (*E*,*Z*,*Z*)-bilindione were obtained in a *ca.* 1:1 ratio, and both isomers were isolated and characterized by ^{1}H NMR, MS, and UV−vis spectroscopy. The double bond configurations of (*Z*,*Z*,*Z*)-5,10,15-triphenylbilindione (**2f**) were confirmed by X-ray crystallographic studies.

Here we report detailed investigations into the oxidation reactions, focusing on the oxidation of substituted FeTPP **1a**−**e** as a synthetic route to triarylbilindiones. We found that *para*-substituted FeTPP **1a**−**d** gave both biladienones and bilindiones both at room temperature and under reflux conditions, whereas unsubstituted FeTPP **1f** gave bilindiones only under reflux conditions. The reason for the different behaviors of unsubstituted FeTPP and substituted FeTPP is unknown. In addition, oxidation at room temperature afforded primarily (*Z*,*Z*,*Z*)-bilindiones, whereas oxidation under reflux conditions afforded an approximately equimolar mixture of (*Z*,*Z*,*Z*)- and (*E*,*Z*,*Z*)-bilindiones.[25] For the preparation of substituted bilindiones, we can perform the coupled oxidation either at room temperature or at an elevated temperature. The isolated yields of (*Z*,*Z*,*Z*)-bilindiones oxidized at room temperature were almost the same as those performed under the reflux conditions. Thus, *para*-substituted (*Z*,*Z*,*Z*)-bilindiones **2a**−**d** were prepared here by coupled oxidation at room temperature. As a typical reaction, a chloroform solution of substituted FeTPP **1a**−**d**, pyridine, and ascorbic acid was stirred with O_2 bubbling at room temperature for 1 h, the reaction mixture was treated with acid, and then biladienone and bilindione were formed. We examined coupled oxidation reactions of [tetrakis(4-methoxycarbonylphenyl)porphyrinato]iron(III) chloride **1a**, [tetrakis(4-dodecyloxycarbonylphenyl)porphyrinato]iron(III) chloride **1b**, [tetrakis(4-cyanophenyl)porphyrinato]iron(III) chloride **1c**, and [tetrakis(2-methoxyphenyl)porphyrinato]iron(III) chloride **1d** to clarify the substituent effects on the reaction (Scheme 2). These porphyrins gave the oxidized linear tetrapyrroles with different polarity and different hydrophobicity. Thus reaction conditions and workup procedures such as acid treatment conditions and chromatographic separation were optimized for each preparation. *para*-Substituted bilindiones **2a**−**d**, *ortho*-substituted bilindione **2e**, and *ortho*-substituted biladienone **3e** are new compounds, while compounds **2f**, **3a**−**d**, and **3f** were reported previously.[14,25]

The most difficult aspect of the linear tetrapyrrole synthesis via coupled oxidation is the fact that several products of various oxidation levels and their *Z*-*E* isomers were formed during the oxidation,[25] so that the development of efficient separation of these was necessary. Biladienone was the most nonpolar compounds among the products, thus chromatographic separation of the mixture on silica gave biladienone as the first fraction. Separation of biladienone was straightforward, and it was obtained in yields ranging 15−70%. Bilindione is much more polar than biladienone, and the polarity of bilindione is similar to that of a few byproducts. Separation of bilindione from these byproduct was tedious for some bilindiones. Careful chromatographic separation on a neutral silica gel column afforded bilindiones. Use of alumina column gave efficient separation of tri(4-methoxyphenyl)bilindione **2d** from a red byproduct with similar polarity.

The dipole moments calculated with ab initio MO (B3LYP/6-311+G(d,p)) were 6.6 D, 1.1 D, 5.7 D, and 4.1 D for **2a**, **2c**, **2d**, and **2f**, respectively. The dipole moments are displayed in Figure 1. Dipole moments of **2a**, **2d**, and **2f** are on the pseudoplane of the tetrapyrroles, while that of **2c** is out of plane. The electron-withdrawing substituents, cyano groups, on the aryl rings counteract the original dipole moment of the bilindione core. Bilindione **2d** having the electron-donating substituents is rather polar, and elution from the silica gel column was slow.

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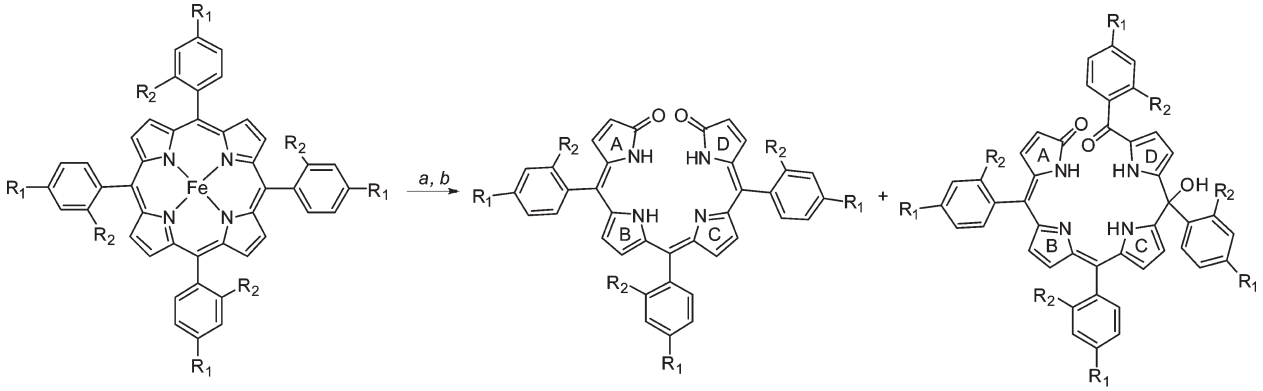
Scheme 2. Coupled Oxidation of [Tetraarylporphyrinato]iron(III) Chloride[a]



[a] Conditions: (*a*) ascorbic acid, O_2, pyridine, rt, 1 h; (*b*) 2 M HCl or 2 M HCl + TFA.

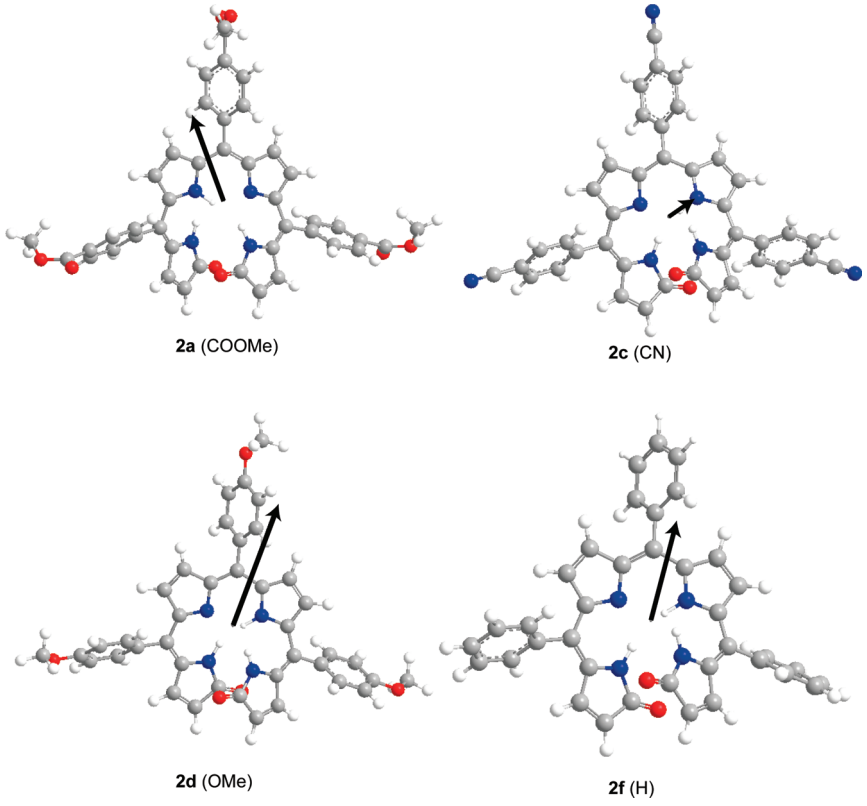


Figure 1. Dipole moments determined with ab initio molecular orbital calculations at B3LYP/6-311+G(d,p).

The isolated yields of bilindione were 6%, 19%, 7%, and 2% for **2a**, **2b**, **2c**, and **2d**, respectively. Although these yields were not satisfactory, a single-step synthesis and no report on other synthetic routes to this class of compounds make the reaction worth studying.

There is a clear tendency in yields of bilindiones and biladienones that the yields of biladienones increased as the substituents on the aryl groups are electron-donating, while the yields of bilindiones increased as the substituents are electron-withdrawing. The yields of *para*-substituted arylbiladienones were 85% (OMe), 59% (H), 44% (COOMe), and 28% (CN).[14] The isolated yields of *para*-substituted aryl bilindiones were 2% (OMe), 4% (H), 6% (COOMe), and 7% (CN) (see Table 1). For the preparation of bilindiones, use of tetraarylporphyrin carrying electron-withdrawing groups is preferred.

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Structures of these compounds were confirmed by ^{1}H NMR, 1D-difference NOE, 2D-NMR (^{1}H−^{1}H COSY and HMBC), ^{13}C NMR, and mass spectroscopy. Within the NMR time scale, bilindione has C_2 symmetry due to the rapid NH proton exchange between the B-ring and the C-ring, and thus the ^{1}H NMR pattern was simple. Characteristic signals of bilindiones were four doublets appearing in the region 6.1−7.0 ppm, which were assigned to the pyrrole β-protons. The configurations of the double bonds of all bilindiones were assigned to *Z*,*Z*,*Z* because NMR patterns of the bilindiones were similar to those of (*Z*,*Z*,*Z*)-**2e** whose structure was confirmed by X-ray crystallography.[25]

Acid Treatment of the Reaction Mixture. The reaction mixture just after the reaction of iron porphyrin with O_2, ascorbic acid, and pyridine was dark brown. When acid was added, the mixture turned gradually dark blue, indicating that the iron was replaced with proton and π-conjugated linear tetrapyrroles were produced. The acid treatment procedure also affected the yield of bilindiones and biladienones. As an acid, we attempted to use hydrochloric acid, sulfuric acid, trifluoroacetic acid, and a combination of these. Treatment of the chloroform solution of the reaction mixture with HCl_{aq} or H_2SO_{4aq} in a two-phase system was a mild process and suitable for preparation of **2a**, **2c**, **2d**, **3a**, **3c**, and **3d**. The reaction rate was very slow for hydrophobic substrate such as **1b**, and the color change was incomplete. Therefore addition of trifluoroacetic acid was necessary to prepare **2b** and **3b**. For other cases, however, use of HCl or H_2SO_4 gave better yields of products.

Coupled Oxidation of *ortho*-Substituted [Tetraarylporphyrinato]iron(III) Chloride. We previously reported that coupled oxidation of [tetramesitylporphyrinato]iron(III) chloride did not proceed owing to the steric hindrance of the *o*-methyl groups.[25] We attempted to cleave iron tetraarylporphyrin carrying one *ortho* substituent in each phenyl group. The coupled oxidation of [tetra(2-methoxyphenyl)porphyrinato]iron(III) chloride **1e** proceeded smoothly to afford both biladienone **3e** (14% yield) and bilindione **2e** (10% yield).

Decrease in the absorbance in the Soret band of FeTPP followed the first order kinetics in the presence of pyridine, ascorbic acid, and O_2 in chloroform. The rate of bleaching of the Soret band of the iron tetraarylporphyrin depended on the concentration of pyridine. In the absence of pyridine, the bleaching rate was very low. For unsubstituted tetraphenylporphyrin and *para*-substituted tetraphenylporphyrins, the rate increased with increasing pyridine concentrations and saturated at the pyridine concentration of *ca.* 1.5 M.[14] In contrast, bleaching of the Soret band of [tetra(2-methoxyphenyl)porphyrinato]iron(III) chloride **1e** proceeded fastest when the concentration of pyridine was 0.13 M, and the bleaching reaction was inhibited at higher pyridine concentrations (Figure 2). We used 0.25 M pyridine for coupled oxidation of **1e** and 2 M pyridine for coupled oxidation of other iron porphyrins.

Molecular Orbital Energy Levels and UV−vis Absorption Spectra of Bilindiones. For application of bilindiones to electronic and optical functional materials, control of the frontier molecular orbital energy by substituents should be important. Electronic effects of substituents introduced in the aryl rings on the electronic structure of bilindiones were examined by molecular orbital studies. In Table 2, molecular orbital energies calculated by PM3[27] and HF/6-31(D)[28] are listed. When the orbital energies of HOMO−1, HOMO, LUMO, and LUMO+1 are compared between **2a** and **2f**, the COOMe groups in **2a** stabilized the energies of all of these MOs to a similar extent, so that the optical excitation energy of **2a** is expected to be similar to that of **2f**. In contrast, the MeO groups in **2d** destabilized the

Table 1. Isolated Yields of Bilindiones and Biladienones Carrying Substituents in the *para* or *ortho* Positions of the 5,10,15-Aryl Groups (2a−f, 3a−f)

substituents in the aryl groups	yield of bilindiones **2** (%)	yield of biladienones **3** (%)
p-OMe	2	85[b]
H[a]	4[c]	59[c]
p-COOMe	6	44[b]
p-COO(CH$_2$)$_{11}$CH$_3$	19	41
p-CN	7	28[c]
o-OMe	10	14

[a] Reaction with O_2 was carried out under reflux conditions for bilindione synthesis. The yield of the (*Z*,*Z*,*Z*)-isomer is shown, although considerable amounts of *Z*,*Z*,*E*-isomer were also formed. For *para*- or *ortho*-substituted bilindiones, coupled oxidation was performed at room temperature, and only (*Z*,*Z*,*Z*)-isomers were isolated. [b] Taken from ref 14. [c] The yields of **2f**, **3f**, and **3c** are different from those reported in ref 25. The yields listed here are more reliable according to the repeated synthesis.

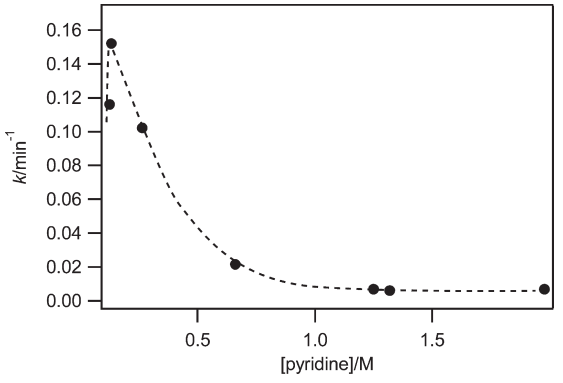

Figure 2. Bleaching rate of [tetra(2-methoxyphenyl)porphyrinato]iron **1e** versus pyridine concentrations.

Table 2. Energy Levels (eV) of Frontier Molecular Orbitals Calculated by PM3 and HF/6-31G(D)

	PM3				HF/6-31G(D)			
	2f (H)	**2d** (OMe)	**2a** (COOMe)	**2c** (CN)	**2f** (H)	**2d** (OMe)	**2a** (COOMe)	**2c** (CN)
HOMO−1	−8.823	−8.735	−9.206	−9.404	−8.152	−7.850	−8.415	−8.855
HOMO	−8.023	−8.020	−8.370	−8.720	−6.819	−6.724	−6.819	−7.467
LUMO	−3.271	−3.270	−3.659	−2.155	0.643	0.719	0.643	−0.050
LUMO+1	−2.640	−2.623	−3.044	−1.359	1.983	2.041	1.983	1.328

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Table 3. Absorption Maxima and Oscillator Strength of Bilindiones Obtained by Molecular Orbital Calculations[a]

	λ_{max}/nm (oscillator strength)	coefficients of CI (%)	λ_{max}/nm (oscillator strength)	coefficients of CI (%)
2f (H)	379 (1.250)	HOMO−1 to LUMO (64%) HOMO to LUMO+1 (26%)	570 (0.257)	HOMO−LUMO (94%)
2d (OMe)	385 (1.368)	HOMO−1 to LUMO (52%) HOMO to LUMO+1 (38%)	568 (0.262)	HOMO−LUMO (94%)
2a (COOMe)	380 (1.218)	HOMO−1 to LUMO (65%) HOMO to LUMO+1 (22%)	572 (0.267)	HOMO−LUMO (94%)
2c (CN)	332 (0.468)	HOMO to LUMO+1 (83%)	438 (0.657)	HOMO−LUMO (96%)

[a] Calculated by MOS-F program, CNDO/S3 CI(20,20).

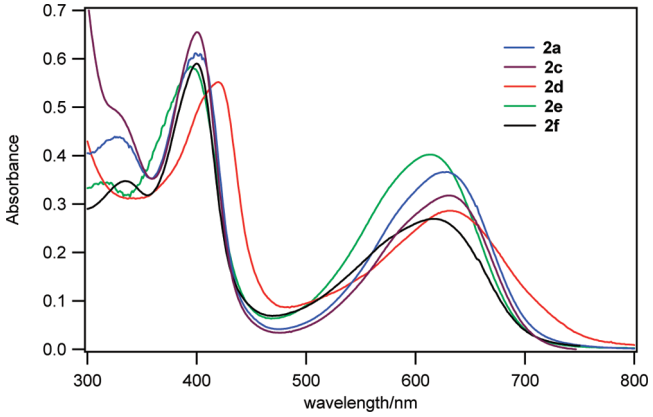

Figure 3. UV−vis spectra of bilindiones **2a**, **2c**, **2d**, **2e**, and **2f** in $CHCl_3$. The absorption maxima were 399 and 626 nm (**2a**), 400 and 631 nm (**2c**), 419 and 632 nm (**2d**), 394 and 613 nm (**2e**), and 400 and 616 nm (**2f**).

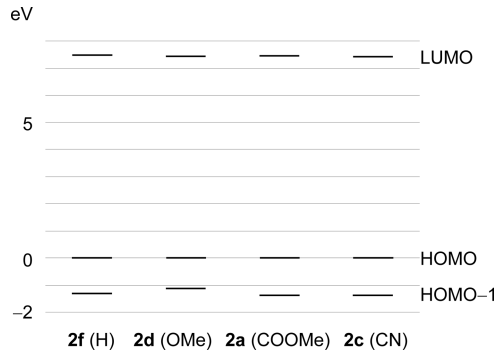

Figure 4. Relative energies of LUMO and HOMO−1 for four bilindiones **2f**, **2d**, **2a**, and **2c** calculated at HF/6-31G(D). In order to compare the excitation energy, the energy levels referenced to the HOMO level are shown.

HOMO−1 energy, whereas they do not affect the energies of other MOs to a significant extent. This explains the red-shift in the optical absorption of **2d** involving the HOMO−1 molecular orbital (vide infra).

Figure 3 shows UV−vis spectra of five bilindiones, **2a**, **2c**, **2d**, **2e**, and **2f**, in chloroform. Solutions of **2a**, **2b**, **2c**, **2e**, and **2f** were blue, while that of **2d** was greenish blue. The higher energy band of the UV−vis spectra of **2d** was red-shifted by 21 nm from 399 to 420 nm. The molecular orbital calculations of these bilindiones by using MOS-F indicated that the absorption maximum of **2f** was 379 nm as compared to that of **2d** at 385 nm (Table 3). According to the configuration interaction (CI) calculations, the higher energy band at around 400 nm consists of the mixture of excitations from HOMO−1 to LUMO and HOMO to LUMO+1, while the lower energy band at around 600 nm consists of mainly excitation from HOMO to LUMO. The CI calculation of **2c** gave completely different assignment from other bilindiones. The origin of the discrepancy between the CI calculation and the observed spectra for **2c** is not known. As shown in Figure 4, the HOMO−1 energy level of **2d** was destabilized compared to **2a**, **2c**, and **2f**, and this explains the red-shift of the higher energy band of **2d**. Figure 3 also shows that **2e** having methoxy groups in the *ortho* position showed similar absorption maxima to those of **2f**. According to the optimized structures by HF/6-31G(D), the phenyl groups in **2e** were nearly perpendicular to the dipyrromethane plane: the dihedral angles of pyrrole-α, *meso* carbon, phenyl 1C and phenyl 2C were −73°, −74°, and −72°. The dihedral angles of other bilindiones **2a**, **2c**, **2d**, and **2f** were −49°, −51°, −53° for **2a**, −66°, −59°, −75° for **2c**, −53°, −48°, −50° for **2d**, and −54°, −51°, and −51° for **2f**, allowing π-electrons to partially delocalize between the aryl groups and the bilin core. The difference in the dihedral angles can explain the fact that the *o*-methoxy groups in **2e** have minor electronic effects on the molecular orbitals localized on the bilin core, and thus the effects on the UV−vis spectrum were undetectable.

CONCLUSIONS

Triarylbilindiones with either COOMe, $COOC_{12}H_{25}$, CN, or OMe in the *para* position of the aryl groups were prepared by the coupled oxidation of the corresponding iron porphyrin in yields ranging from 2% to 19%. There was a tendency that the electron-withdrawing groups favor formation of bilindione, whereas electron-donating groups favor formation of biladienone. The substituents in the *para* positions affected polarity of the oxidized products, and thus isolation procedures and the properties of bilindiones were dependent on the substituents. In particular, the substituents in the *para* position affected the frontier molecular orbital energies of bilindione π-orbitals, and these were confirmed by MO calculations and UV−vis spectroscopic studies. Triarylbilindione and tetraarylbiladienone carrying one *o*-OMe group in each aryl group were also prepared similarly by coupled oxidation. The reactions demonstrated that the coupled oxidation of tetraarylporphyrin can be extended to the derivatives with *ortho* substituents.

EXPERIMENTAL SECTION

Molecular orbital calculations were performed using MOPAC 3.0 Pro (Fujitsu Ltd.) and Gaussian 09 (Gaussian Inc.).[28] Commercially available reagents were used as received. Chromatographic separations of bilindiones were performed using silica gel 60N, spherical neutral with particle size 40−50 μm, Kanto Chemical Company. Iron porphyrins were prepared by refluxing a DMF solution of porphyrin and iron(II) chloride for 4 h. Assignments of ^{1}H NMR and ^{13}C NMR were performed using ^{1}H−^{1}H COSY, NOESY, 1D-differential NOE spectra, HMBC, and HSQC spectra. Preparation and spectroscopic data of biladienones **3a**, **3c**, **3d**, and **3f** and bilindione **2f** were reported elsewhere.[24,25]

(4*Z*,9*Z*,15*Z*)-5,10,15-Tri(4-methoxycarbonylphenyl)-(21*H*,-23*H*,24*H*)-1,19,21,24-tetrahydro-1,19- bilindione (2a). Chloroform (300 mL) was placed in a 1-L three-necked flask, and O_2 was bubbled for 30 min. [5,10,15,20-Tetra(4-methoxycarbonylphenyl)porphyrinato]iron(III) chloride **1a** (1.5 g), ascorbic acid (5.7 g), and pyridine (66 mL) were added, and the mixture was stirred at room temperature for 1 h with O_2 bubbling. The reaction was quenched by adding 2 M HCl (500 mL), and the solution was stirred for 1 h at room temperature. The chloroform solution was separated and washed with water twice, and the organic layer was dried over Na_2SO_4. After the Na_2SO_4 was filtered off, the organic layer was evaporated to give a mixture of biladienone, bilindione, and other pigments. Bilindione was isolated by silica gel column chromatography eluted with chloroform/acetone (95:5). Further purification by silica gel column chromatography using dichloromethane/acetone (17:3) followed by silica gel column chromatography using chloroform yielded 69 mg (5.9%) of bilindione. ^{1}H NMR (500 MHz, chloroform-*d*): δ 3.85 (s, 6H, CH_3), 3.97 (s, 3H, CH_3), 6.26 (d, J = 5.8 Hz, 2H, pyrrole H-2), 6.47 (d, J = 4.55 Hz, 2H, pyrrole H-7), 6.69 (d, J = 4.55 Hz, 2H, pyrrole H-8), 6.94 (d, J = 5.8 Hz, 2H, pyrrole H-3), 7.45 (d, J = 8.45 Hz, 4H, 5,15-phenylene H-2′), 7.60 (d, J = 8.40 Hz, 2H, 10-phenylene H-2′), 8.04 (d, J = 8.45 Hz, 4H, 5,15-phenylene H-3′), 8.17 (d, J = 8.45 Hz, 2H, 10-phenylene H-3′). ^{13}C NMR (125 MHz, chloroform-*d*): δ 171.4, 153.2, 143.1, 139.0, 138.2, 130.2, 124.8, 121.8 ppm. MS (MALDI-TOF): m/z 732 [M$^+$]. HRMS (FAB): calcd for $C_{43}H_{32}O_8N_4$ m/z 732.2220, found 732.2198. UV−vis spectrum: λ_{max} (ε_{max}) 328 nm (2.56×10^4 M^{-1} cm^{-1}), 399 nm (3.86×10^4 M^{-1} cm^{-1}), 626 nm (2.08×10^4 M^{-1} cm^{-1}).

(4*Z*,9*Z*,15*Z*)-5,10,15-Tri(4-dodecyloxycarbonylphenyl)-(21*H*,23*H*,24*H*)-1,19,21,24-tetrahydro-1,19-bilindione (2b). Chloroform (100 mL) was placed in a 500-mL three-necked flask, and O_2 was bubbled for 30 min. [5,10,15,20-Tetra(4-dodecyloxycarbonylphenyl)porphyrinato]iron(III) chloride **1b** (102 mg), ascorbic acid (0.58 g), and pyridine (10 mL) were added, and the mixture was stirred at room temperature for 1 h with O_2 bubbling. The reaction was quenched by adding trifluoroacetic acid (6 mL) and 6 M HCl (100 mL), and the solution was stirred for 30 min. The chloroform solution was separated and washed with water six times, and the organic layer was dried over Na_2SO_4. After the Na_2SO_4 was filtered off, the organic layer was evaporated to give a mixture of biladienone, bilindione, and other pigments. Bilindione was isolated by silica gel column chromatography eluted with chloroform/acetone (95:5). Biladienone was obtained in the earlier fraction (40.3 mg, 40.7%). Bilindione eluted in the later fraction was further purified by silica gel column chromatography using dichloromethane/acetone (9:1). The bilindione fraction was further purified by preparative silica gel TLC using chloroform, to yield 14.5 mg (18.5%) of bilindione. ^{1}H NMR (500 MHz, chloroform-*d*): δ 0.87 (t, J = 6.25 Hz, 9H, CH_3), 1.22−1.39 (m, 54H, CH_2), 1.73 (m, 4H, CH_2), 1.80 (m, 2H, CH_2), 4.28 (t, J = 6.25 Hz, 4H, CH_2), 4.38 (t, J = 6.25 Hz, 2H, CH_2), 6.26 (d, J = 5.8 Hz, 2H, pyrrole), 6.46 (d, J = 4.55 Hz, 2H, pyrrole), 6.70 (d, J = 4.55 Hz, 2H, pyrrole), 6.95 (d, J = 5.8 Hz, 2H, pyrrole), 7.45 (d, J = 8.45 Hz, 4H, phenylene), 7.60 (d, J = 8.40 Hz, 2H, phenylene), 8.04 (d, J = 8.45 Hz, 4H, phenylene), 8.15 (d, J = 8.45 Hz, 2H, phenylene). ^{13}C NMR (125 MHz, chloroform-*d*): δ 171.4, 153.3, 143.2, 139.0, 137.7, 130.2, 124.7, 121.9 ppm. MS (MALDI-TOF): m/z 1195 [M$^+$]. HRMS (FAB): calcd for $C_{76}H_{98}O_8N_4$ m/z 1194.7385, found 1194.7380. UV−vis spectrum: λ_{max} (ε_{max}) 326 nm (1.50×10^4 M^{-1} cm^{-1}), 403 nm (2.22×10^4 M^{-1} cm^{-1}), 628 nm (1.05×10^4 M^{-1} cm^{-1}).

(4*Z*,9*Z*,15*Z*)-5,10,15-Tri(4-cyanophenyl)-(21*H*,23*H*,24*H*)-1,19,21,24-tetrahydro-1,19-bilindione (2c). Chloroform (600 mL) was placed in a 2-L two-necked flask, and O_2 was bubbled for 30 min. [5,10,15,20-Tetra(4-cyanophenyl)porphyrinato]iron(III) chloride **1c** (455 mg, 0.567 mmol), ascorbic acid (6.25 g, 3.52×10^{-2} mol), and pyridine (75.2 mL, 0.92 mol) were added, and the mixture was stirred at room temperature for 2 h with O_2 bubbling. The reaction was quenched by adding 2 M HCl (600 mL), and the solution was stirred for 2 h. The chloroform solution was washed with water four times, and the organic layer was dried over Na_2SO_4. After Na_2SO_4 was filtered off, the organic layer was evaporated to give a mixture of biladienone, bilindione, and other pigments. Bilindione was isolated by silica gel column chromatography eluted with chloroform/acetone (15/1). Further purification by silica gel column (chloroform/acetone, 10:1) yielded 24.1 mg (6.7%) of bilindione **2c**. ^{1}H NMR (500 MHz, chloroform-*d*): δ 6.33 (d, J = 5.80 Hz, 2H, pyrrole H-2), 6.50 (d, J = 4.35 Hz, 2H, pyrrole H-7), 6.70 (d, J = 4.35 Hz, 2H, pyrrole H-8), 7.01 (d, J = 5.80 Hz, 2H, pyrrole H-3), 7.51 (d, 4H, J = 8.00 Hz, 5,15-phenylene), 7.64 (d, J = 7.95 Hz, 2H, 10-phenylene), 7.70 (d, J = 8.00 Hz, 4H, 5,15-phenylene), 7.82 (d, J = 7.95 Hz, 10-phenylene. ^{13}C NMR (125 MHz, chloroform-*d*) δ 171.0, 153.2, 143.1, 140.5, 137.6, 132.3, 125.2, 122.3. MS (MALDI-TOF): m/z 634 [MH$^+$]. HRMS (FAB): calcd for $C_{40}H_{23}O_2N_7$ m/z 633.1913, found 633.1901. UV−vis spectrum: λ_{max} (ε_{max}) 400 nm (2.59×10^4 M^{-1} cm^{-1}), 631 nm (1.26×10^4 M^{-1} cm^{-1}).

(4*Z*,9*Z*,15*Z*)-5,10,15-Tri(4-methoxyphenyl)-(21*H*,23*H*,24*H*)-1,19,21,24-tetrahydro-1,19-bilindione (2d). Chloroform (600 mL) was placed in a 2-L two-necked flask, and O_2 was bubbled for 30 min. [5,10,15,20-Tetra(4-methoxyphenyl)porphyrinato]iron(III) chloride **1d** (494.4 mg, 0.600 mmol), ascorbic acid (5.49 g, 3.09×10^{-2} mol), and pyridine (68.4 mL, 0.84 mol) were added, and the mixture was stirred at room temperature for 4 h with O_2 bubbling. The reaction was quenched by adding 2 M HCl (900 mL), and the solution was stirred for 2 h. The chloroform solution was washed with water four times, and the organic layer was dried over Na_2SO_4. After Na_2SO_4 was filtered off, the organic layer was evaporated to give a mixture of biladienone, bilindione, and other pigments. Bilindione was isolated by silica gel column chromatography eluted with chloroform/acetone (30/1). Further purification by preparative silica gel TLC (chloroform/acetone, 20:1) yielded 7.7 mg (1.9%) of bilindione **2d**. ^{1}H NMR (500 MHz, chloroform-*d*): δ 3.77 (s, 6H, CH_3), 3.90 (s, 3H, CH_3), 6.20 (d, J = 5.0 Hz, 2H, pyrrole H-2), 6.50 (d, J = 4.0 Hz, 2H, pyrrole H-7), 6.77 (d, J = 4.0 Hz, 2H, pyrrole H-8), 6.87 (d, J = 10.0 Hz, 4H, 5,15-phenylene H-3′), 6.99 (overlapped two doublets, 4H, pyrrole H-3 and 5-phenylene H-3′), 7.29 (d, J = 10.0 Hz, 4H, 5,15-phenylene H-2′), 7.47 (d, J = 10.0 Hz, 2H, 10-phenylene H-2′). ^{13}C NMR (125 MHz, chloroform-*d*) δ 171.6, 153.3, 143.3, 139.8, 138.1, 130.1, 123.7, 121.3 ppm. MS (MALDI-TOF): m/z 649 [MH$^+$]. HRMS (FAB): calcd for $C_{40}H_{32}O_5N_4$ m/z 648.2373, found 648.2373. UV−vis spectrum: λ_{max} (ε_{max}) 419 nm (2.35×10^4 M^{-1} cm^{-1}), 632 nm (1.08×10^4 M^{-1} cm^{-1}).

(4*Z*,9*Z*,15*Z*)-5,10,15-Tri(2-methoxyphenyl)-(21*H*,23*H*,24*H*)-1,19,21,24-tetrahydro-1,19-bilindione (2e) and (4*Z*,9*Z*)-1,-15,21,24-Tetrahydro-19-(2-methoxybenzoyl)-15-hydroxy-5,-10,15-tris(2-methoxyphenyl)-23*H*-bilin-1-one (3e). Chloroform (500 mL) was placed in a 2-L three-necked flask, and O_2 was bubbled for 60 min. [5,10,15,20-Tetra(2-methoxyphenyl)porphyrinato]iron(III) chloride **1e** (39 mg), ascorbic acid (0.49 g), and pyridine (10.6 mL) were added, and the mixture was stirred at room temperature for 4 h with O_2 bubbling. The reaction was quenched by adding 2 M HCl (500 mL), and the solution was stirred for 24 h. The chloroform solution was washed with

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water four times, and the organic layer was dried over Na_2SO_4. After the Na_2SO_4 was filtered off, the organic layer was evaporated to give a mixture of biladienone, bilindione, and other pigments. Bilindione and biladienone were separated by silica gel column chromatography eluted with chloroform. Further purification by silica gel column chromatography using dichloromethane/acetone (95:5) yielded 5.4 mg (14%) of **3e** and 3.3 mg (10.0%) of **2e**.

Data for 3e. ^{1}H NMR (500 MHz, acetone-d_6): δ 3.70−3.80 (m, 12H, CH_3), 5.85−5.87 (m, 1H, pyrrole), 6.00 (d, J = 4.55 Hz, 1H, pyrrole), 6.04 (*s*, 1H; OH), 6.17 (*m*, 1H; pyrrole), 6.23−6.26 (*m*, 1H; pyrrole), 6.42−6.44 (m, 1H; pyrrole), 6.54−6.55 (m, 1H; pyrrole), 6.79 (s, 1H; pyrrole), 6.83 (*s*, 1H; pyrrole), 6.90−7.48 (m, 16H; phenyl), 10.2 (*s*, 1H, NH), 10.7 (*d*, J = 31.1 Hz, 1H, NH), 12.9 (*s*, 1H, NH). ^{13}C NMR (125 MHz, acetone-d_6) δ 183.4, 172.2, 138.2, 134.3, 125.8, 124.2, 122.3, 118.7, 111.3, 108.6, 74.6 ppm. MS (TOF): m/z 785 $[M + H]^+$, 767 $[M - OH]^+$. HRMS (FAB): calcd for $C_{48}H_{39}O_6N_4$ m/z 767.2870, found 767.2889. UV−vis spectrum: λ_{max} (ε_{max}) 326 nm (3.40×10^4 M^{-1} cm^{-1}), 560 nm (2.29×10^4 M^{-1} cm^{-1}).

Data for 2e. ^{1}H NMR (500 MHz, chloroform-*d*): δ 3.72 (*s*, 9H; CH_3), 6.14 (*d*, J = 5.80, 2H; NH), 6.31 (*d*, J = 4.50 Hz, 2H; NH), 6.51 (*d*, J = 3.90 Hz, 2H; NH), 6.83 (*d*, J = 5.20 Hz, 2H; CH_2), 6.92−7.75 (*m*, 12H; phenyl). ^{13}C NMR (125 MHz, chloroform-*d*) δ 171.9, 138.7, 137.8, 130.2, 124.0, 120.6 ppm. MS (TOF): m/z = 648 $[M]^+$. HRMS (FAB): calcd for $C_{40}H_{32}O_5N_4$ m/z 648.2373, found 648.2390. UV−vis spectrum: λ_{max} (ε_{max}) 394 nm (2.69×10^4 M^{-1} cm^{-1}), 613 nm (1.92×10^4 M^{-1} cm^{-1}).

■ ASSOCIATED CONTENT

Supporting Information. ^{1}H NMR of **2a**, **2b**, **2c**, **2d**, and **2e**; ^{13}C NMR of **2a**, **2b**, **2c**, **2d**, **2e**, and **3e**; tables of ^{13}C NMR chemical shifts of the major signals of **2a**−**f** and **3e**−**f**; atomic coordinates of **2a**, **2c**, **2d**, and **2f** optimized at the B3LYP/6-31G(D) level. This material is available free of charge via the Internet at http://pubs.acs.org.

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