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De Novo Synthesis of Long-Wavelength Absorbing Chlorin-13,15-dicarboximides

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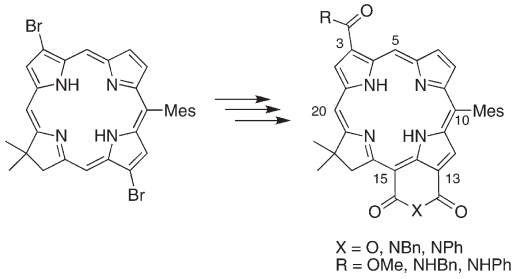

Chlorins bearing a six-membered imide ring spanning positions 13−15, commonly referred to as purpurinimides, exhibit long-wavelength absorption yet have heretofore only been available via semisynthesis from naturally occurring chlorophylls. A concise route to synthetic chlorins, which bear a geminal dimethyl group in the pyrroline ring, has been extended to provide access to chlorin-13,15-dicarboximides. The new route entails (i) synthesis of a 13-bromochlorin, (ii) palladium-catalyzed carbamoylation at the 13-position, (iii) regioselective 15-bromination under acidic conditions, and (iv) one-flask palladium-mediated carbonylation and ring closure to form the imide. In some cases the ring closure reaction afforded the isomeric (and readily separable) chlorin−isoimide in addition to the chlorin−imide. The resulting chlorin−imides and chlorin−isoimides exhibit long-wavelength absorption (679−715 nm) and emission (683−720 nm) in the far-red and near-infrared spectral region. The absorption of the chlorin−(iso)imides fills the spectral window between that of analogous synthetic chlorins and 13^1-oxophorbines (603−687 nm) and bacteriochlorins (707−792 nm). The synthetic versatility of the de novo route complements the existing semisynthetic route from chlorophylls and should enable fundamental spectroscopic studies and photochemical applications.

Introduction

Chlorophylls possess a five-membered exocyclic ring spanning the 13- and 15-positions. The exocyclic ring contains an oxo moiety at the 13^1-position and a methoxycarbonyl substituent at the 13^2-position. The electron-withdrawing 13-keto group embedded in the exocyclic ring (termed the isocyclic ring) is conjugated with the macrocyclic π-system, and causes a significant hyperchromic and bathochromic shift of the long-wavelength absorption band. The position and strength of the long-wavelength absorption band not only affect the spectral coverage but also are key determinants of the energy and properties of the excited singlet state. Thus, alteration of the keto group in the isocyclic ring can be used to modify the spectral and excited-state properties of the chlorophyll molecules.

Synthetic manipulation of chlorophylls—both early degradative methods as well as constructive modifications that continue in the present era—have focused on alteration of the isocyclic ring.[1,2] Conant and Moyer first reported that treatment of methyl pheophorbide *a* in ether with methanolic KOH afforded a series of chlorins, of which two purplish brown substances were isolated and termed "phaeopurpurins 7 and 18".[3] Fischer identified the respective compounds as originating from oxidative opening of the isocyclic ring[4] to give a chlorin-13,15-dicarboxylic acid and a chlorin bearing a

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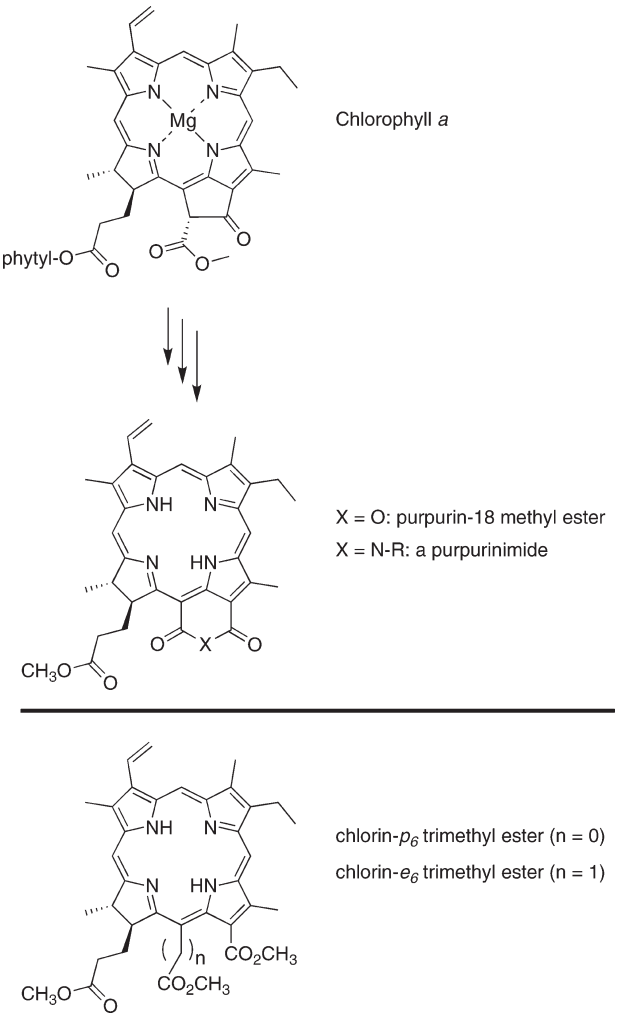
six-membered anhydride ring.[4,5] Fischer further constructed the six-membered imide ring from the chlorin−anhydride "purpurin-18" and its methyl ester[6,7] to give the corresponding purpurinimide[8,9] (hereafter referred to as a chlorin−imide[10]).

In the 1990s, Smith carried out a variety of modifications to purpurin-18 as well as the related chlorin-e_6 and chlorin-p_6 analogues (Scheme 1).[11,12] He also showed that the *N*-alkyl chlorin−imide derivative exhibited the long-wavelength absorption band at 706 nm, a position bathochromically shifted with respect to that of the parent chlorophyll macrocycle.[12] The shift of the absorption band in the chlorin−imide to longer wavelength made the compounds attractive for a number of reasons, particularly as photosensitizers in photodynamic therapy (PDT). In PDT, the use of light sources with wavelengths in the red or near-infrared region enables deep penetration of tissue,[13] which in turn places a premium on photosensitizers that are active in the red or near-infrared spectral region. In more recent years, the groups of Mironov and of Pandey have significantly expanded the scope of chlorin−imides,[14−27] including extension

SCHEME 1



to bacteriochlorin−imides derived from bacteriochlorophyll *a*.[28−34] The chlorin−imides have been used chiefly as photosensitizers in PDT[18,35,36] although several studies have been carried out related to artificial photosynthesis.[20,22−24,37] Limited spectroscopic studies to date suggest that the presence

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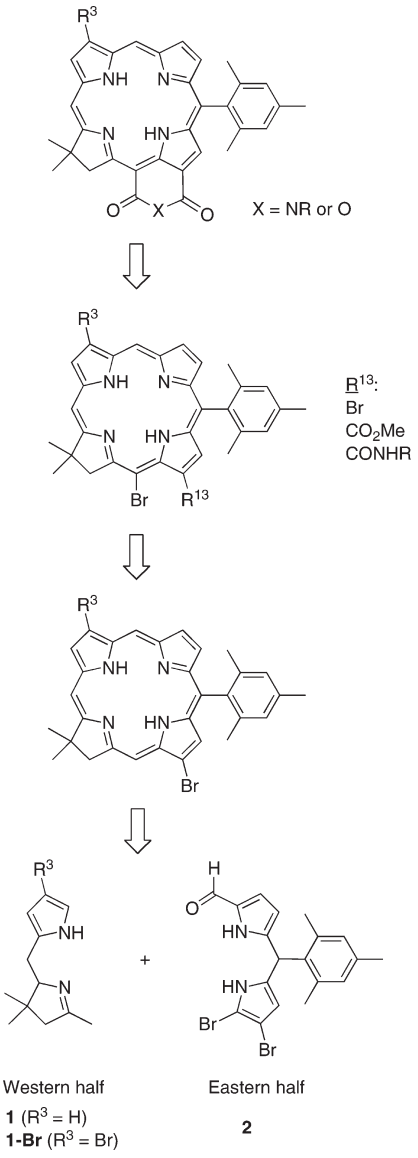
of the six-membered imide ring does not significantly alter the excited-state lifetime of the chlorin.[38]

A chief attraction of chlorin−imides is the ability to introduce diverse groups at the nitrogen of the imide ring. In addition, the presence of the second carbonyl group (at the 15-position) further stabilizes the macrocycle toward routine handling as evidenced by the variety of reported imidation reactions and subsequent applications. Thus, the ready availability of purpurin-18 from chlorophyll *a*, the bathochromic shift and stability upon imide formation, and the diverse imide *N*-substituents that can be introduced together render such chlorin−imides quite attractive for a number of applications.

On the other hand, the only methods for the synthesis have relied on the modification of naturally occurring chlorophylls. The modification of the isocyclic ring usually entails (1) base-promoted, oxidative ring-opening (allomerization) to produce the corresponding diacid and (2) conversion of the resulting diacid (or diester) to the anhydride or imide. The chief limitation of this method stems not from the transformation of the isocyclic ring itself, but rather the constraints imposed by the nearly full complement of substituents at the β-pyrrolic positions of the naturally occurring macrocycles. To our knowledge there are no reports concerning the de novo synthesis of chlorin−imides.[39] To fulfill the potential of chlorin−imides in applications as diverse as solar energy conversion, PDT, and fluorescence bioimaging requires the ability to tailor the macrocycle at will without constraints imposed by the substituents present in the parent chlorophyll structure.

Here we report a de novo synthesis of chlorin−imides. The synthetic route builds from the strategies we have developed over the years for the de novo synthesis[40−42] of chlorins and their subsequent elaboration.[43−46] The chlorins bear a geminal dimethyl group in the pyrroline ring to stabilize the macrocycle toward adventitious dehydrogenation. The new synthetic route entails the Pd-mediated derivatization of 13-bromochlorins to introduce the methoxycarbonyl or carbamoyl group, (2) regioselective 15-bromination of the resulting 13-substituted chlorins, and (3) a one-flask Pd-mediated carbonylation followed by ring closure. The resulting chlorin−imides bear 0 or 1 β-pyrrolic substituents and hence constitute sparsely substituted analogues of the naturally derived "purpurinimides" described above. This simple route to tailorable chlorin−imides should allow systematic studies of their fundamental spectroscopic and photochemical properties.

SCHEME 2



Results and Discussion

I. Retrosynthetic Analysis. A retrosynthetic approach to chlorin-13,15-dicarboximides is outlined in Scheme 2. The route to 3,13-disubstituted chlorins relies on the known reaction of Western and Eastern halves.[42] Very recently we also developed a method for regioselective 15-bromination of the chlorin.[46] Thus, the key issues for extension of established routes to the chlorin−imides concern the nature and order of the carbonylative reactions at the 13- and 15-positions. In initial studies we intended to prepare the chlorin bearing alkoxycarbonyl substituents at both the 13- and 15-positions of the macrocycle, and build the six-membered imide ring from the corresponding diacid following saponification of the ester groups. Eventually, we settled on a one-flask Pd-catalyzed carbonylation of the 13-carbamoyl-15-bromo-substituted chlorin to form the imide ring. The latter approach

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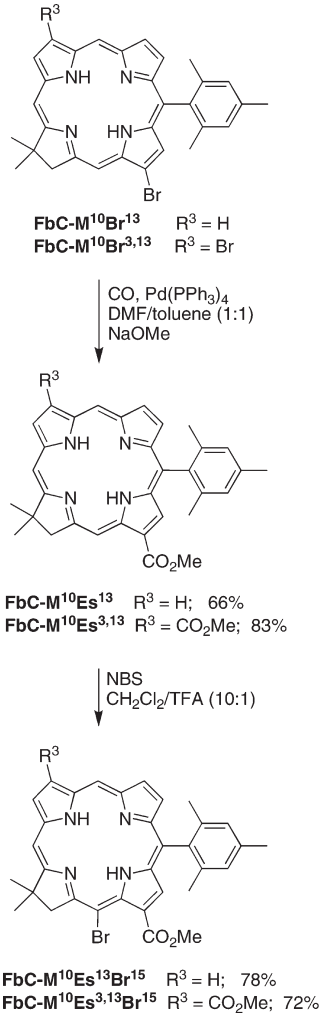
proved to be more efficient and afforded the expected product in fewer steps.

II. Synthesis. A. Alkoxycarbonylation of Chlorins. One starting chlorin contains the 18,18-dimethyl group, a 10-mesityl group, and a 13-bromo group; this chlorin is denoted **FbC-M^{10}Br^{13}**. A second chlorin contains in addition a 3-bromo substituent and is denoted **FbC-M^{10}Br^{3,13}**. Streamlined methods[42,47] were applied to gain access to substantial quantities of the known[46] bromo-chlorin **FbC-M^{10}Br^{13}** (in 38% yield from 1.0 mmol of **1**[48] and **2**[43]) and the new dibromochlorin **FbC-M^{10}Br^{3,13}** (in 25% yield from 0.5 mmol of **1-Br**[49] and **2**). The starting 3-bromo- or 3,13-dibromo-substituted chlorin was subjected to Pd-mediated carbonylation with use of CO and $Pd(PPh_3)_4$ in DMF/toluene followed by addition of NaOMe to give the corresponding 3-methoxycarbonyl or 3,13-bis(methoxycarbonyl)chlorin (Scheme 3). In this manner, chlorin-13-monoester **FbC-M^{10}Es^{13}** and chlorin-3,13-diester FbC-M^{10}Es^{3,13} were obtained in 66% and 83% yield, respectively.

Prior studies of the regioselectivity of bromination of chlorins showed an overlay of steric effects of substituents at specific sites on the intrinsic electronic reactivity of the chlorin.[46] Thus, under neutral conditions, 13-unsubstituted chlorins undergo bromination regioselectively at the 15-position, whereas 10,13-substituted chlorins undergo bromination preferentially at the 7-position. On the other hand, acidic conditions suppress reaction at the 7-position, and the 10,13-substituted chlorin undergoes bromination regioselectively at the 15-position.[46] Such studies were performed with chlorins bearing 13-acetyl or 13-bromo substituents. Here, treatment of 13-ester-substituted chlorins **FbC-M^{10}Es^{13}** and **FbC-M^{10}Es^{3,13}** with NBS in acidified CH_2Cl_2 also afforded regioselective 15-bromination to give **FbC-M^{10}Es^{13}Br^{15}** (78%) and **FbC-M^{10}Es^{3,13}Br^{15}** (72%) (Scheme 3).

One-flask palladium-catalyzed reactions that form cyclic imides from the corresponding haloesters,[50−52] dibromo compounds,[53,54] or even monoesters[55] have been described. Initially, we investigated this general approach to install the six-membered imide ring. Thus, formation of the imide ring was attempted by reaction of **FbC-M^{10}Es^{13}Br^{15}** with CO and benzylamine (or propylamine) under various conditions [e.g., $Pd(PPh_3)_4$ in toluene/DMF; $Pd(OAc)_2$/Xantphos/Et_3N in toluene; $Pd(OAc)_2/PPh_3/Cs_2CO_3$ in toluene]. This approach proved to be fruitful in certain cases (see below). Attempts at a one-flask installation of the imide ring on dibromochlorin[46] **FbC-M^{10}Br^{13,15}** were unsuccessful (see the Supporting Information). Accordingly, we pursued other approaches for installing the imide ring on 3-unsubstituted chlorins, as described in the next sections.

SCHEME 3



B. Chlorin−Diester and Chlorin−Anhydride Formation. The chlorin-13,15-diester **FbC-M^{10}Es^{13,15}** was sought as an intermediate to introduce the imide unit. After investigation of a number of conditions, we found that reaction of monobromo/monoester chlorin **FbC-M^{10}Es^{13}Br^{15}** with CO in THF/MeOH containing $Pd(PPh_3)_4$ and K_2CO_3 afforded the desired diester **FbC-M^{10}Es^{13,15}** (Scheme 4). Efforts to hydrolyze both methoxycarbonyl groups were unsuccessful; however, one ester was hydrolyzed, and upon coupling with a primary amine, yielded the corresponding chlorin−imide (see the Supporting Information for exploratory studies and data). Although the stepwise route to the chlorin−diester **FbC-M^{10}Es^{13,15}** did not provide a viable route to the chlorin−imide, the chlorin−diester **FbC-M^{10}Es^{13,15}** was quite attractive for spectroscopic examination.

The synthesis of chlorin-13,15-dicarboxylic anhydride also was pursued. Thus, monoester chlorin **FbC-Es^{13}Br^{15}** was subjected to carbonylation with CO in the presence of a stoichiometric amount of $Pd(PPh_3)_4$ in DMF/toluene. Subsequent treatment of the resulting acylpalladium intermediate with aqueous NaOH afforded chlorin−anhydride **FbC-M^{10}An** in 21% yield (Scheme 4). Alternatively the chlorin−anhydride **FbC-M^{10}An** was obtained in 21% yield together with a large amount of debrominated starting material

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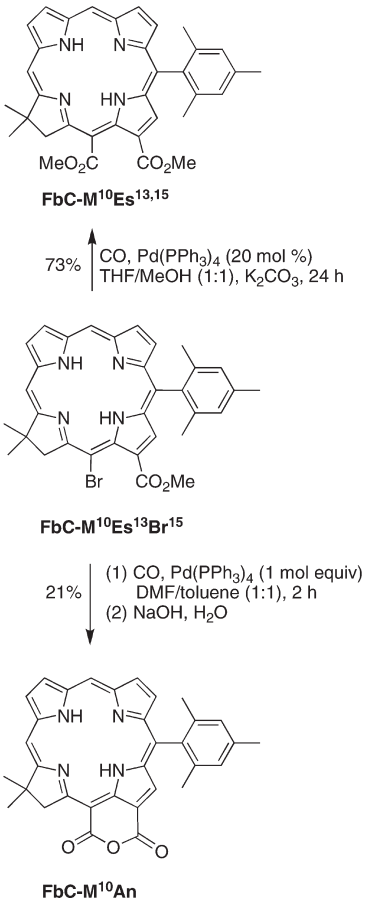
SCHEME 4



(66%) with use of CO, a stoichiometric amount of $Pd(PPh_3)_4$, Cs_2CO_3, and H_2O (2 equiv) in THF. The chlorin−anhydride **FbC-M^{10}An** provides a valuable benchmark for spectroscopic comparison with the previously described anhydride (i.e., purpurin-18) derived from chlorophyll *a*. However, with the goal of forming the corresponding chlorin−imides, we sought a more direct approach for installing the imide ring. Thus, we turned to the corresponding 13-carbamoyl-substituted chlorins rather than 13-ester substituents.

C. Carbamoylation of Chlorins. The starting 3-bromo- or 3,13-dibromo-substituted chlorin also was subjected to Pd-mediated reaction in the presence of CO and a primary amine to introduce the carbamoyl unit. Recently, we employed analogous palladium-catalyzed carbamoylation to tailor the perimeter of synthetic bacteriochlorins.[56] This method requires a stoichiometric amount of palladium. Upon application to the chlorins here, satisfactory results were obtained in some cases, but in other cases double carbonylation (yielding an oxalamide moiety) as well as multiple products were observed. For example, treatment of the 13-bromochlorin **FbC-M^{10}Br^{13}** to the Pd-mediated carbonylation conditions in the absence of an amine followed by propylamine afforded the double-carbonylated, oxalamide-substituted chlorin **FbC-M^{10}(COCmPr)^{13}** in 38% yield (eq 1). While this result illustrates the richness of this chemistry, the requirement for a stoichiometric amount of palladium

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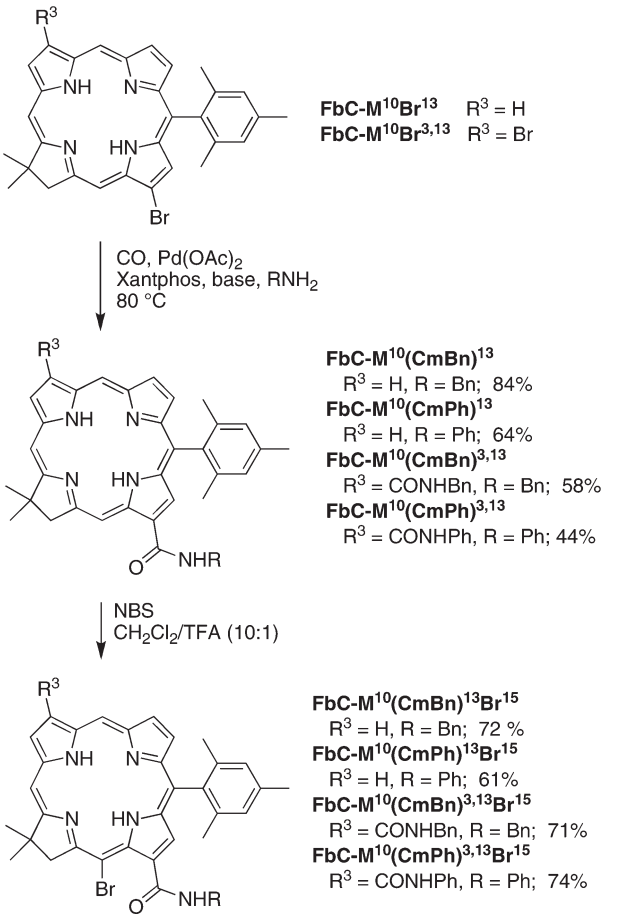
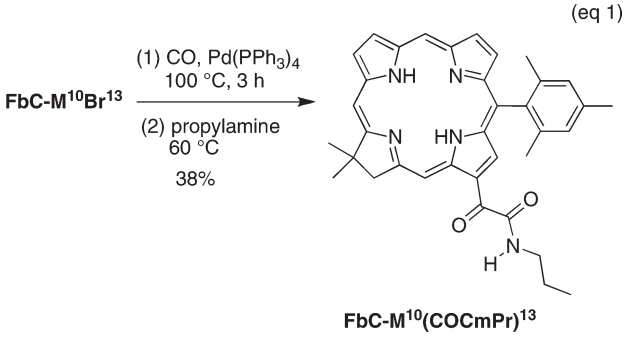
SCHEME 5



was a significant drawback; therefore, we explored different conditions for the carbamoylation process.



Numerous conditions and catalytic systems have been reported for Pd-catalyzed alkoxycarbonylation or carbamoylation,[50−55,57−59] although few are applicable for a low (atmospheric) pressure of CO. In addition, Pd-mediated coupling reactions with tetrapyrrole macrocycles typically are carried out in quite dilute solution.[60,61] We found modified Buchwald

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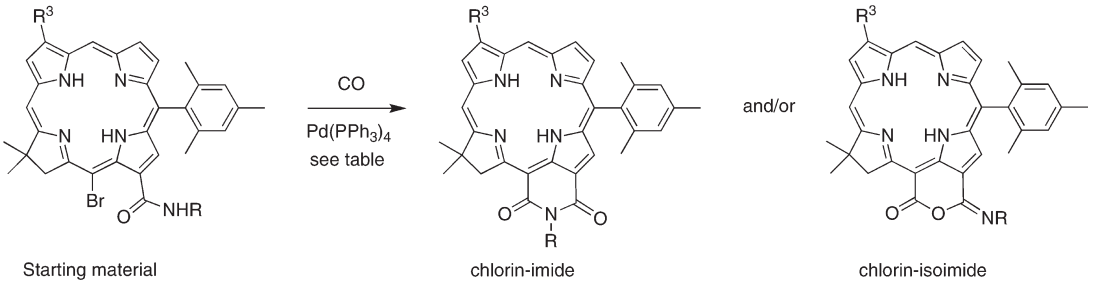
TABLE 1. Carbonylation−Intramolecular Amidation To Give Chlorin−Imides and/or Chlorin−Isoimides



entry	starting material	reaction conditions[a]	reaction products (% yield) chlorin−imide	chlorin−isoimide	other
1	**FbC-M^{10}(CmBn)^{13}Br^{15}** (R^3 = H, R = Bn)	A	**FbC-M^{10}I-Bn** 50%	—[b]	—[c]
2	**FbC-M^{10}(CmBn)^{13}Br^{15}** (R^3 = H, R = Bn)	B	**FbC-M^{10}I-Bn** Trace	**FbC-M^{10}Iso-Bn** 55%	—[b]
3	**FbC-M^{10}(CmPh)^{13}Br^{15}** (R^3 = H, R = Ph)	B	**FbC-M^{10}I-Ph** Trace	**FbC-M^{10}Iso-Ph** 59%	—[b]
4	**FbC-M^{10}(CmPh)^{13}Br^{15}** (R^3 = H, R = Ph)	C	**FbC-M^{10}I-Ph** 45%	—[b]	—[d]
5	**FbC-M^{10}(CmBn)^{3,13}Br^{15}** (R^3 = CONHBn, R = Bn)	B	**FbC-(CmBn)^{3}M^{10}I-Bn** 32%	**FbC-(CmBn)^{3}M^{10}Iso-Bn** 26%	—[b]
6	**FbC-M^{10}(CmPh)^{3,13}Br^{15}** (R^3 = CONHPh, R = Ph)	B	**FbC-(CmPh)^{3}M^{10}I-Ph** 72%	—[b]	—[b]

[a]Reaction conditions: (A) $Pd(PPh_3)_4$ (1 equiv), CO, toluene/DMF (1:1), no base. (B) $Pd(PPh_3)_4$ (1 equiv), CO, toluene, Cs_2CO_3 (3 equiv). (C) $Pd(PPh_3)_4$ (20 mol %), CO, toluene, Cs_2CO_3 (3 equiv). [b]Not observed. [c]Debrominated starting material (**FbC-M^{10}(CmBn)^{13}**) was observed in 50% yield. [d]Traces of unreacted starting material and debrominated starting material (**FbC-M^{10}(CmPh)^{13}**) also were observed.

conditions[50] [CO balloon pressure, $Pd(OAc)_2$ (15−30 mol %), Xantphos (15−30 mol %), Et_3N or Cs_2CO_3 (3−6 mol equiv), and 2−4 equiv of amine in toluene] to be successful. Thus, the reaction of **FbC-M^{10}Br^{13}** or **FbC-M^{10}Br^{3,13}** with benzylamine gave the corresponding 3-*N*-benzylcarbamoylchlorin **FbC-M^{10}(CmBn)^{13}** or 3,13-bis(*N*-benzylcarbamoyl)chlorin **FbC-M^{10}(CmBn)^{3,13}** in 84% or 58% yield, respectively (Scheme 5). Similarly, the reaction of **FbC-M^{10}Br^{13}** with aniline gave **FbC-M^{10}(CmPh)^{13}** in 64% yield. The reaction of **FbC-M^{10}Br^{3,13}** with aniline under similar conditions resulted in a low yield (25%), whereas the reaction in toluene/DMF (1:1) gave **FbC-M^{10}(CmPh)^{3,13}** in 44% yield. In each case, examination of the reaction course (TLC and UV−vis) revealed the formation and subsequent disappearance of unknown intermediates, and the reaction mixture typically contained a small amount of unidentified byproducts. Regardless, the target chlorins were obtained in reasonable yield and in satisfactory purity.

The four 13-carbamoylchlorins were subjected to bromination under acidic conditions,[46] which suppress bromination in ring B (i.e., the 7- and 8-positions) and thereby direct bromination to the 15-position (Scheme 5). Thus, treatment of the chlorin with 1 equiv of NBS in CH_2Cl_2/TFA solution afforded the corresponding 15-bromochlorin in satisfactory yield, together with a small amount of dibromo or monobromo side products. In each case the product was purified upon column chromatography.

D. Ring Closure. The four chlorins bearing 13-carbamoyl and 15-bromo substituents were subjected to a Pd-mediated domino carbonylation−intramolecular amidation reaction. Thus, the reaction of **FbC-M^{10}(CmBn)^{13}Br^{15}** with CO in the presence of a stoichiometric amount of $Pd(PPh_3)_4$ in DMF/toluene (1:1) afforded chlorin−imide **FbC-M^{10}I-Bn** in 50% yield, together with the corresponding debrominated starting material **FbC-M^{10}(CmBn)^{13}** also in 50% yield (Table 1, entry 1). However, the same reaction of **FbC-M^{10}-(CmBn)^{13}Br^{15}** in toluene alone but with Cs_2CO_3 afforded the chlorin−isoimide **FbC-M^{10}Iso-Bn** as the major product with only trace amounts of the desired chlorin−imide **FbC-M^{10}I-Bn** (entry 2). Similarly, treatment of **FbC-M^{10}(CmPh)^{13}Br^{15}** with CO in the presence of a stoichiometric amount of $Pd(PPh_3)_4$ in toluene afforded chlorin−isoimide **FbC-M^{10}Iso-Ph** in 59% yield (entry 3), together with a trace amount of the desired chlorin−imide **FbC-M^{10}I-Ph**. In contrast, use of a catalytic amount of $Pd(PPh_3)_4$ afforded chiefly the desired chlorin−imide without observable amounts of the chlorin−isoimide (entry 4). The reaction of 3,13-bis(carbamoyl)chlorin **FbC-M^{10}(CmBn)^{3,13}Br^{15}** in the presence of a stoichiometric amount of $Pd(PPh_3)_4$ in toluene afforded both the desired chlorin−imide (32%) and the chorin−isoimide (26%) (entry 5). However, the same conditions applied to 3,13-bis(carbamoyl)chlorin **FbC-M^{10}-(CmPh)^{3,13}Br^{15}** afforded the chlorin−imide as the only observable product in 72% yield (entry 6). Finally, we note that in some cases, particularly with stoichiometric amounts of the palladium reagent, the crude reaction mixture showed trace amounts of palladium chelated chlorin (upon LD-MS analysis), which could be separated from the free base chlorins by column chromatography and was not further analyzed.

In summary, the Pd-mediated carbonylative ring closure tends to afford a mixture of the chlorin−imide and chlorin−isoimide in unpredictable ratio. While methods for the conversion of isoimides into imides are known,[21,33,62] most employ strong base, which we sought to avoid. One attempt to convert the chlorin−isoimide **FbC-(CmBn)^{3}M^{10}Iso-Bn** into the corresponding chlorin−imide **FbC-(CmBn)^3-M^{10}I-Bn** via C−N rearrrangement upon refluxing in toluene did not result in any noticeable isomerization. The formation of the 6-membered isoimide ring apparently stems from nucleophilic attack of the carbonyl oxygen on the intermediate acyl-palladium species. Such transformations

(62) Kozyrev, A. N.; Zheng, G.; Zhu, C.; Dougherty, T. J.; Smith, K. M.; Pandey, R. K. *Tetrahedron Lett.* **1996**, *37*, 6431–6434.

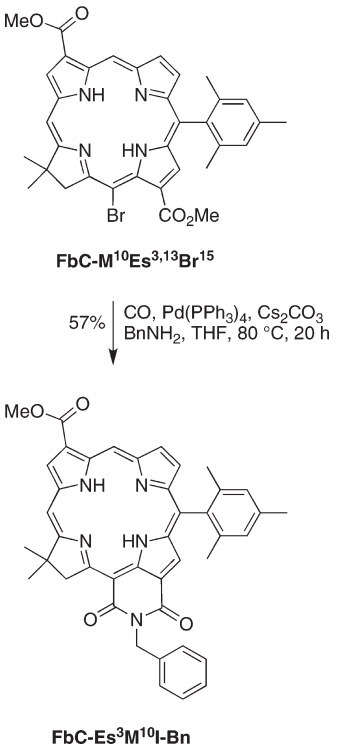
are precedented in palladium-catalyzed reactions as well as in reaction of carboxylic acid derivatives of chlorophylls with amines.[21] Key spectral features for distinguishing the isomers are described below.

E. Chlorin−Imide with a Distinct 3-Substituent. The aforementioned methods afford the chlorin−imide lacking a 3-substituent or bearing a 3-carbamoyl substituent. In the latter case, the 3-carbamoyl substituent is identical with that initially employed at the 13-position to construct the imide ring. Here we sought to prepare a chlorin−imide bearing a different auxochrome at the 3-position, namely a 3-methoxycarbonyl group. Thus, the 3,13-bis(methoxycarbonyl)chlorin bearing a 15-bromo group (**FbC-M^{10}Es^{3,13}Br^{15}**) was subjected to Pd-mediated carbamoylation with benzylamine in THF containing $Pd(PPh_3)_4$ and Cs_2CO_3. Under these conditions the corresponding chlorin−imide **FbC-Es^{3}M^{10}I-Bn** was obtained in 57% yield (Scheme 6). Attempted imide formation with benzylamine with use of $Pd(OAc)_2$, 1,3-bis(diphenylphosphino)propane, and Cs_2CO_3 in toluene (or $Pd(PPh_3)_4$ and Et_3N in DMF/toluene) resulted mainly in the corresponding debrominated starting material (**FbC-M^{10}Es^{3,13}**). No chlorin−isoimide was observed.

III. Characterization. The new chlorin−anhydride, chlorin−imides, and chlorin−isoimides were characterized by ^{1}H NMR (and in some cases ^{13}C NMR and 2D NOESY) spectroscopy, mass spectrometry (ESI-MS and/or LD-MS), and UV−vis absorption and emission spectroscopy. To obtain absolute proof of the putative chlorin−imide and chlorin−isoimide structures, a number of samples (including free base and zinc chelates) were examined under different conditions to obtain suitable crystals for X-ray analysis. X-ray crystal structures were obtained for the free base chlorin−isoimides **FbC-M^{10}Iso-Bn** and **FbC-M^{10}Iso-Ph**, and the zinc chelate chlorin−imide **ZnC-M^{10}I-Ph** [obtained by the reaction of **FbC-M^{10}I-Ph** with $Zn(OAc)_2$]. In each case the X-ray data confirmed the proposed structures for the chlorin−imide and chlorin−isoimides (see the Supporting Information). The X-ray crystal structure of **FbC-M^{10}Iso-Bn** revealed *Z* stereochemistry of the isoimide moiety, as has been reported for other (nonchlorin) isoimides.[63] We are not aware of prior single-crystal X-ray data to establish the structure of chlorin−imides versus chlorin−isoimides. While X-ray characterization was unambiguous, a more accessible method for distinguishing the isomers was sought, as described in the next section.

A. Chlorin−Imide versus Chlorin−Isoimide. Three pairs of isomers (chlorin−imide and chlorin−isoimide) were examined to identify simple means of spectroscopic distinction (Chart 1). The UV−vis absorption spectra of the three pairs of isomers are shown in Figure 1. The long wavelength Q_y absorption band of the chlorin−imides (blue) and the chlorin−isoimides (magenta) varies only slightly for a given pair of isomers. However, the ratio of the peak intensity of the Q_y and the B band maximum (I_{Q_y}/I_B) is greater for the chlorin−isoimides (0.61−0.68) versus that of the chlorin−imides (0.43−0.56). Such a distinction, while apparently consistent, is insufficient for reliable structural identification. Attempts to differentiate between the chlorin−imide **FbC-M^{10}I-Bn** and the chlorin−isoimide **FbC-M^{10}Iso-Bn** by using IR spectroscopy were inconclusive, as the spectra were

SCHEME 6



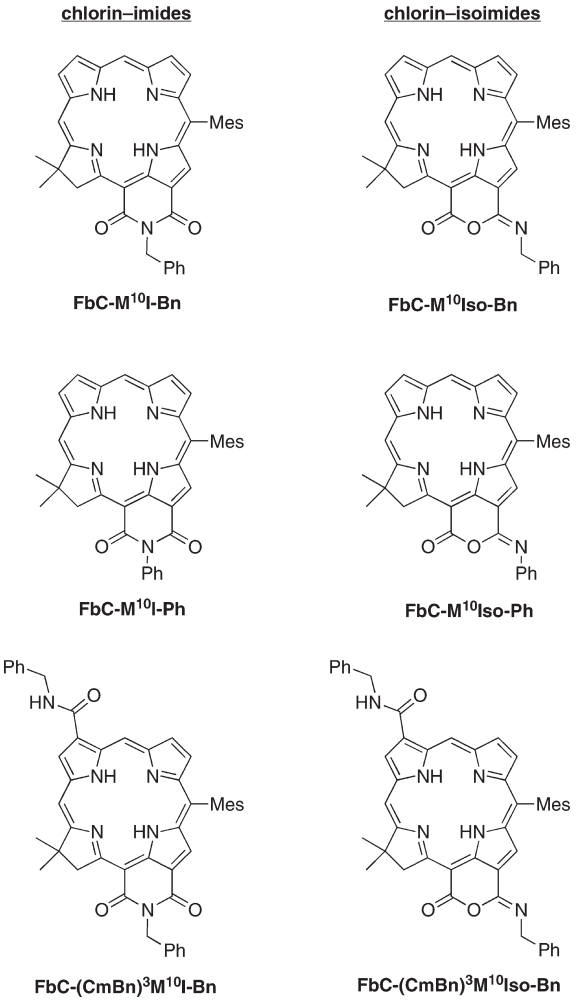
quite complex and there were no sharp distinctions in the IR spectra of the two compounds (see spectra in the Supporting Information).

The chlorin−imide and chlorin−isoimide isomeric pairs exhibited quite similar ^{1}H NMR spectra; however, one key distinction was evident in each pair examined: the chemical shifts of the two pyrrolic N−H protons for the chlorin−imide resonate further downfield (δ 0.58 to 0.08 ppm) compared to those of the corresponding chlorin−isoimide (0.07 to −0.41 ppm). In other words, the chemical shift of the pyrrolic N−H protons for the chlorin−imides is not shifted upfield to the extent typical of chlorins. Typically, the pyrrolic N−H chemical shifts for synthetic chlorins without an exocyclic ring range from −2.0 to −1.0 ppm with a separation ($\Delta\delta$) of the two resonances for the distinct N−H protons (for all chlorins where substituents give rise to C_s symmetry) ranging from 0 to 0.4 ppm. For comparison, the chemical shifts for the two pyrrolic NH protons of the 13^1-oxophorbine **FbOP-M^{10}** (a synthetic chlorin containing a 5-membered isocyclic ring spanning positions 13 and 15, vide infra)[46] are quite far apart (−1.41 and 1.13 ppm; $\Delta\delta$ = 2.54 ppm). The results demonstrate the effect of a given exocyclic ring spanning positions 13 and 15 on the ring current of the chlorin macrocycle. The chemical shifts and differences in chemical shifts for the pyrrolic NH protons of the chlorin−imides, chlorin−isoimides, nonbrominated precursors and the previously reported 13^1-oxophorbine **FbOP-M^{10}** are listed in Table 2.

A literature search did not provide any precedence for such a direct comparison of chlorin−imide and chlorin−isoimide isomers. However, a similar downfield shift of the resonance of the N−H protons was reported for a bacteriochlorin−imide versus that of the bacteriochlorin−isoimide,[33] as well as for a

(63) Corrie, J. E. T.; Moore, M. H.; Wilson, G. D. *J. Chem. Soc., Perkin Trans. 1* **1996**, 777–781.

CHART 1. Chlorin−Imide and Chlorin−Isoimide Isomeric Pairs



porphyrin−imide versus that of the corresponding porphyrin−isoimide.[64] (^{1}H NMR spectroscopy has also been used to assign the structures of two bacteriochlorin−isoimide isomers.[33]) In general, naturally derived chlorin−imides have been reported to show chemical shifts for the two N−H protons in the range of −0.69 to 1.04 ppm.[12,15−17,21−23,25,26] For the most part, the $\Delta\delta$ of the resonances for the two N−H protons in a given chlorin−imide was $<\sim$0.2 ppm (and in some cases only a single peak was noted[15,17,21,22,25,26]).

In summary, the most accessible operational means of distinguishing chlorin−imide and chlorin−isoimide isomers appears to be the difference in chemical shifts of the resonances due to the pyrrolic NH protons. In the case of the *N*-benzyl isomers, the chemical shift of the benzylic $-CH_2-$ protons provides a further distinction: the resonance occurs at ~5.6 ppm for the chlorin−imides **FbC-M^{10}I-Bn** and **FbC-(CmBn)^{3}M^{10}I-Bn** versus ~5.2 ppm for the corresponding chlorin−isoimides **FbC-M^{10}Iso-Bn** and **FbC-(CmBn)^3-M^{10}Iso-Bn**. On the other hand, other regions of the ^{1}H NMR spectra, as well as the ^{13}C NMR spectra vary only slightly and inconsistently for the corresponding pairs of isomers, and thus do not provide diagnostic tools for their distinction.

(64) Kozyrev, A. N.; Zheng, G.; Lazarou, E.; Dougherty, T. J.; Smith, K. M.; Pandey, R. K. *Tetrahedron Lett.* **1997**, *38*, 3335–3338.

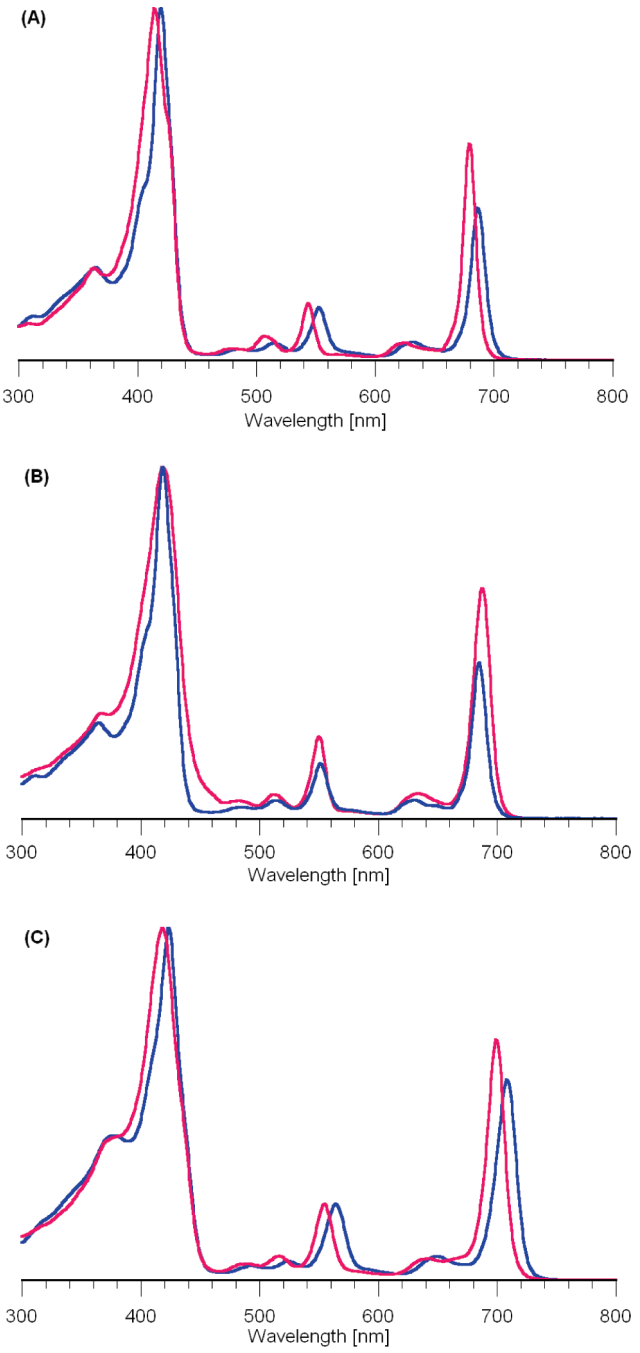


FIGURE 1. Absorption spectral features of chlorin−imides versus chlorin−isoimides (in toluene at room temperature, normalized at the B bands): (A) **FbC-M^{10}I-Bn** (blue), **FbC-M^{10}Iso-Bn** (magenta); (B) **FbC-M^{10}I-Ph** (blue), **FbC-M^{10}Iso-Ph** (magenta); and (C) **FbC-(CmBn)^{3}M^{10}I-Bn** (blue), **FbC-(CmBn)^{3}M^{10}Iso-Bn** (magenta).

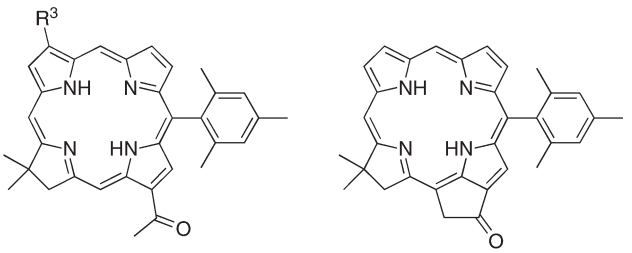
B. Absorption Spectral Properties. The chlorin−imides exhibit many absorption spectral features typical of chlorins, with strong absorption in the blue region (B band) and a moderately strong long-wavelength absorption band (Q_y band) in the red region. The long-wavelength absorption band is relatively sharp with a full-width-at-half-maximum (fwhm) of 15−18 nm. The emission spectra of this class of compounds mirror the long-wavelength absorption band, with a narrow $Q_y(0,0)$ band (fwhm 17−18 nm) and a comparatively weak $Q_y(0,1)$ transition. The Stokes shifts range from 5 to 8 nm (see spectra in the

TABLE 2. Comparison of Pyrrolic NH ^{1}H NMR Chemical Shifts of Chlorin Derivatives[a]

compd	pyrrolic NH δ (ppm)	$\Delta\delta$ (ppm)
	chlorin precursors	
FbC-M^{10}(CmBn)^{13}	−1.74, −1.44	0.30
FbC-M^{10}(CmPh)^{13}	−1.67, −1.35	0.32
FbC-M^{10}(CmBn)^{3,13}	−1.42	0
FbC-M^{10}(CmPh)^{3,13}	−1.48	0
	chlorin−imides	
FbC-M^{10}I-Bn	0.08, 0.43	0.35
FbC-M^{10}I-Ph	0.15, 0.58	0.43
FbC-(CmBn)^{3}M^{10}I-Bn	0.09, 0.29	0.20
FbC-(CmBn)^{3}M^{10}I-Ph	0.19, 0.42	0.23
	chlorin−isoimides	
FbC-M^{10}Iso-Bn	−0.55, −0.12	0.43
FbC-M^{10}Iso-Ph	−0.41, 0.07	0.48
FbC-(CmBn)^{3}M^{10}Iso-Bn	−0.41, −0.15	0.26
	13^1-oxophorbine	
FbOP-M^{10}	−1.41, 1.13	2.54

[a]All spectra were obtained in $CDCl_3$.

Supporting Information). The sharp absorption band renders these compounds well suited for use in energy-transfer cascades,[65] where a series of chromophores with distinct energy levels can be constructed, or polychromatic flow cytometry,[66] where a palette of spectrally distinct absorbers/emitters is desired. A key requirement for such applications is the ability to tune the position of the long-wavelength absorption band in a systematic manner. Here we first consider the spectral effects caused by placement of various carbonyl substituents at the 3- and/or 13-positions of the chlorin, and then consider the spectra of chlorins bearing various exocyclic rings. The 13-acetylchlorin[46] **FbC-M^{10}A^{13}**, 3,13-diacetylchlorin[67] **FbC-M^{10}A^{3,13}**, and 13^1-oxophorbine[46] **FbOP-M^{10}** are included for comparison.



FbC-M^{10}A^{13} R^3 = H
FbC-M^{10}A^{3,13} R^3 = Ac

FbOP-M^{10}

1. Effects of Carbonyl Substituents. The spectral properties of the 13- and 3,13-substituted chlorins are listed in Table 3. Several comparisons concerning the effects of various carbonyl substituents at the 13- or 3,13-positions of the chlorins are as follows: (1) The introduction of a carbonyl substituent at the 13-position results in a bathochromic shift of the Q_y band versus that of the 13-unsubstituted chlorin **FbC-M^{10}** (λ_{Qy} = 637 nm).[67] The bathochromic shift increases in the series carbamide < ester < ketone < oxalamide (Figure 2A). The bathochromic shift is accompanied by a relative increase of the peak intensity of the Q_y versus B band ratio (I_{Q_y}/I_B). (2) Substitution at the 3-position causes an increase in the I_{Q_y}/I_B ratio for the same substituents. (3) The installation of substituents at the 3-position causes an additional bathochromic shift of 390, 542, or 618 cm^{-1} for the carbamide, ester, or ketone, respectively. (4) The magnitude of the bathochromic shift reflects the electron-withdrawing ability of the group attached to the carbonyl moiety in substituents at the 13-position (amino < alkoxy < alkyl < carbamide).

TABLE 3. Absorption and Emission Spectral Properties of Chlorins with 3- and/or 13-Substituents[a]

compd	$\lambda_{Q_y(0,0)}$ (fwhm)/nm	I_{Q_y}/I_B	λ_{em} (fwhm)/nm
FbC-M^{10}A^{13}	659 (12)	0.50	662 (13)
FbC-M^{10}Es^{13}	653 (11)	0.51	656 (12)
FbC-M^{10}(CmBn)^{13}	652 (13)	0.46	656 (13)
FbC-M^{10}(CmPh)^{13}	654 (14)	0.48	658 (15)
FbC-M^{10}(COCmPr)^{13}	671 (19)	0.61	677 (19)
FbC-M^{10}A^{3,13}	687 (16)	0.76	693 (17)
FbC-M^{10}Es^{3,13}	677 (14)	0.77	681 (14)
FbC-M^{10}(CmBn)^{3,13}	669 (18)	0.55	675 (17)
FbC-M^{10}(CmPh)^{3,13}	673 (21)	0.59	681 (16)

[a]In toluene at room temperature.

The introduction of an ester substituent at the 15-position (**FbC-M^{10}Es^{13,15}**) has a negligible effect (bathochromic shift of only 70 cm^{-1}) on the position of the Q_y band versus the corresponding 15-unsubstituted chlorin **FbC-M^{10}Es^{13}**, but does significantly diminish the relative intensity of the Q_y band (Figure 2B). On the other hand, ring closure to give the chlorin−anhydride **FbC-M^{10}An** causes a significant bathochromic shift (538 cm^{-1}) versus the corresponding chlorin−diester **FbC-M^{10}Es^{13,15}**. This observation illustrates the effect of the spatial arrangement and electron-withdrawing features of the carbonyl groups at the 13- and 15-positions in determining the spectroscopic properties of the chlorin.

2. Nature of the Exocyclic Ring. The availability of the chlorin−anhydride, chlorin−imides, and chlorin−isoimides enables a systematic comparison of the effects of various exocyclic rings on the position of the long-wavelength absorption band. The spectral properties of **FbC-M^{10}An** and three pairs of chlorin−imides and chlorin−isoimides are listed in Table 4 (see the Supporting Information for spectra). A set of compounds with common substituents (10-mesityl and a geminal dimethyl group in the pyrroline ring) but with various exocyclic rings includes the oxophorbine (656 nm), chlorin−anhydride (680 nm), *N*-phenyl chlorin−imide (685 nm), and *N*-phenyl chlorin−isoimide (687 nm). Thus, the presence of the imide or isoimide ring causes a substantial bathochromic shift versus that of the oxophorbine. It is noteworthy that *N*-hydroxy chlorin−imides (derivatives of chlorophylls) have been reported to give a further ~9-nm bathochromic shift versus the *N*-H analogue.[68]

3. Outlook. The position of the long-wavelength absorption band of a photochemically active species is of utmost importance, defining not only a spectral region where absorption occurs but also the energy level of the initially

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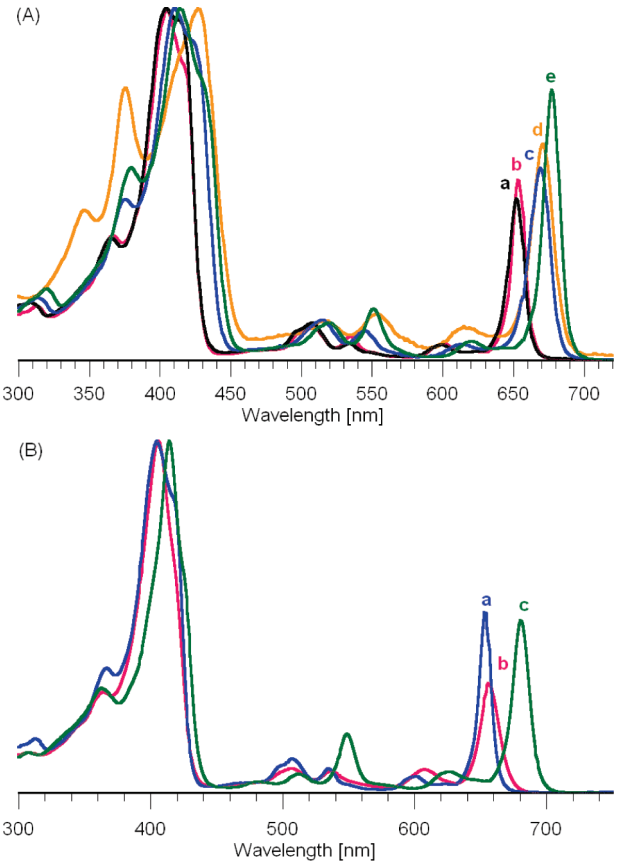


FIGURE 2. Absorption spectra of chlorins (in toluene at room temperature, normalized at the B bands). (A) Comparison of 3- and 3,13-substituted chlorins: **FbC-M^{10}(CmBn)^{13}** (black, a), **FbC-M^{10}-Es^{13}** (magenta, b), **FbC-M^{10}(CmBn)^{3,13}** (blue, c), **FbC-M^{10}(CO-CmPr)^{13}** (orange, d), and **FbC-M^{10}Es^{13,15}** (green, e). (B) Comparison of carbonyl-substituted chlorins: monoester−chlorin **FbC-M^{10}Es^{13}** (blue, a), diester−chlorin **FbC-M^{10}Es^{13,15}** (magenta, b), and chlorin−anhydride **FbC-M^{10}An** (green, c).

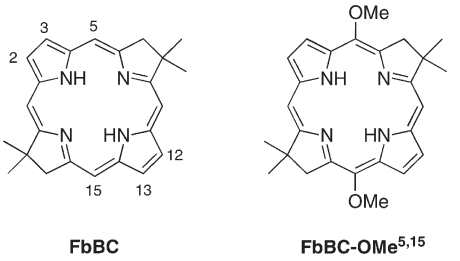
formed excited state. In this regard, the chlorin−imides and chlorin−isoimides fill a crucial window in the far-red/near-infrared spectral region. Prior studies with synthetic chlorins have shown that the position of the long-wavelength Q_y absorption band could be shifted from 603 nm (for the zinc complex of the chlorin lacking any β-pyrrolic or meso substituents)[42] to 687 nm (for **FbC-M^{10}A^{3,13}**).[67] By varying the number and position of substituents at the perimeter of the synthetic chlorins, the absorption spectral properties could be tuned within that spectral region with few-nanometer precision.[43,47,67,69−73] Although the presence of the isocyclic ring (e.g., **FbOP-M^{10}**, $\lambda_{Q_y(0,0)}$ = 656 nm) afforded a substantial bathochromic shift relative to that of the unsubstituted chlorin,[46] investigation of a wide variety of substituents has not yet revealed design strategies for pushing the Q_y absorption band into the near-infrared region.

TABLE 4. Absorption and Emission Spectral Properties of Chlorins Bearing Various Exocyclic Rings[a]

compd	$\lambda_{Q_y(0,0)}$ (fwhm)/nm	I_{Q_y}/I_B	λ_{em} (fwhm)/nm
FbOP-M^{10}	656 (11)	0.63	660 (12)
FbC-M^{10}Iso-Bn	679 (13)	0.61	683 (15)
FbC-M^{10}An	680 (15)	0.49	685 (17)
FbC-M^{10}I-Ph	685 (14)	0.44	690 (17)
FbC-M^{10}I-Bn	686 (15)	0.43	691 (16)
FbC-M^{10}Iso-Ph	687 (17)	0.65	693 (17)
FbC-(CmBn)^{3}M^{10}Iso-Bn	699 (18)	0.67	705 (17)
FbC-(CmBn)^{3}M^{10}I-Bn	708 (19)	0.56	713 (19)
FbC-(CmPh)^{3}M^{10}I-Ph	709 (19)	0.60	716 (19)
FbC-Es^{3}M^{10}I-Bn	715 (17)	0.69	720 (18)

[a]In toluene at room temperature.

On the other hand, the position of the long-wavelength absorption band in synthetic bacteriochlorins ranges from 717 nm for the bacteriochlorin **FbBC** lacking any β-pyrrolic or meso substituents[74] to 785−792 nm for 3,13-bis(chalcone)-substituted bacteriochlorin analogues thereof.[73] As with chlorins, the presence of a variety of auxochromes at the β-pyrrolic (2,3,12,13) or 5,15 (meso) positions enables tuning of the Q_y band with few-nanometer precision within this spectral region.[56,73−77] Recently, the introduction of methoxy substituents at the 5- and 15-positions (**FbBC-OMe^{5,15}**) was found to cause a hypsochromic shift of the Q_y band, giving absorption at 707 nm.[78]



FbBC **FbBC-OMe^{5,15}**

Thus, the present spectral region that is accessible via de novo synthesized bacteriochlorins is 707−792 nm. The spectral region left untouched by prior chlorins or bacteriochlorins (687−707 nm) is nicely matched by the chlorin−(iso)-imides, which absorb strongly in the region 686−715 nm. Thus, the chlorin−(iso)imides fill a spectral window that lies between that of simple chlorins and bacteriochlorins (Figure 3). In this regard, a series of synthetic tetrapyrrole pigments is now available that affords tunable absorption spanning the red and near-infrared region from 600 to 800 nm.

Experimental Section

I. Streamlined Synthesis of 13-Bromo-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}Br^{13}). A mixture of 2,3,4,5-tetrahydro-1,3,3-trimethyldipyrrin (**1**, 0.19 g, 1.0 mmol) and

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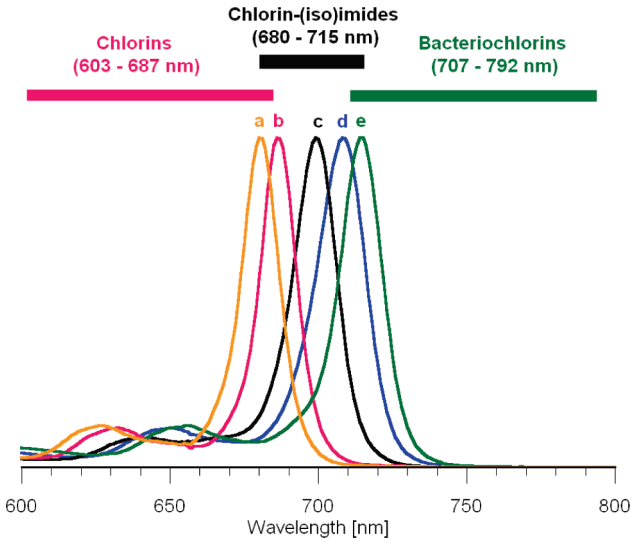

FIGURE 3. Comparison of Q_y region absorption bands of chlorins, chlorin−(iso)imides, and bacteriochlorins. The chlorin−(iso)imides fill a spectral window defined by chlorins and bacteriochlorins. The colors and labels are as follows: chlorin−anhydride **FbC-M^{10}An** (orange, a); chlorin−(iso)imides **FbC-M^{10}I-Bn** (magenta, b), **FbC-(CmBn)^{3}M^{10}Iso-Bn** (black, c), **FbC-(CmBn)^{3}M^{10}I-Bn** (blue, d), and **FbC-Es^{3}M^{10}I-Bn** (green, e). Spectra are in toluene at room temperature.

8,9-dibromo-1-formyl-5-mesityldipyrromethane (**2**, 0.42 g, 0.93 mmol) in CH_2Cl_2 (30 mL) was treated with a solution of $TsOH \cdot H_2O$ (0.95 g, 5.0 mmol) in MeOH (10 mL). The resulting mixture was stirred at room temperature for 30 min. A sample of 2,2,6,6-tetramethylpiperidine (5.0 mL, 29 mmol) was added, and the reaction mixture was concentrated. The resulting yellow-red solid was suspended in CH_3CN (100 mL), to which samples of 2,2,6,6-tetramethylpiperidine (5.1 mL, 30 mmol), anhydrous $Zn(OAc)_2$ (2.75 g, 15.0 mmol), and AgOTf (0.771 g, 3.00 mmol) were added. The resulting mixture was refluxed for 18 h exposed to air, and then concentrated and filtered through silica (CH_2Cl_2). Fractions containing chlorin were collected and concentrated. The resulting blue-green solid was dissolved in CH_2Cl_2 (10 mL), treated with TFA (0.875 mL, 11.4 mmol), and stirred for 4 h. The reaction mixture was treated with saturated aqueous $NaHCO_3$ and stirred vigorously for 5 min. The organic phase was separated, washed (water and brine), dried (Na_2SO_4), and concentrated. Column chromatography [silica, hexanes/CH_2Cl_2 (2:1)] afforded a green solid (0.19 g, 38%). The characterization data (^{1}H NMR, absorption, LD-MS, FAB-MS) were consistent with those reported previously.[46]

3,13-Dibromo-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}Br^{3,13}). A mixture of 8-bromo-2,3,4,5-tetrahydro-1,3,3-trimethyldipyrrin (**1-Br**, 0.134 g, 0.500 mmol) and **2** (0.220 g, 0.500 mmol) in CH_2Cl_2 (15 mL) was treated with a solution of $TsOH \cdot H_2O$ (0.475 g, 2.5 mmol) in MeOH (5 mL). The resulting mixture was stirred at room temperature for 30 min, treated with 2,2,6,6-tetramethylpiperidine (2.5 mL, 14 mmol), and concentrated. The resulting solid was suspended in CH_3CN (50 mL), to which samples of 2,2,6,6-tetramethylpiperidine (2.5 mL, 14 mmol), anhydrous $Zn(OAc)_2$ (1.35 g, 7.50 mmol), and AgOTf (0.385 g, 1.50 mmol) were added. The resulting mixture was refluxed for 18 h exposed to air. The reaction mixture was concentrated and filtered through silica (CH_2Cl_2). Fractions containing chlorin were collected, concentrated, and demetalated with use of TFA as described for **FbC-M^{10}Br^{13}**. Column chromatography [silica, hexanes/CH_2Cl_2 (1:1)] afforded a greenish solid (75.5 mg, 25%): ^{1}H NMR δ −1.78 (br s, 2H), 1.85 (s, 6H), 2.04 (s, 6H), 2.61 (s, 3H), 4.63 (s, 2H), 7.25 (s, 2H), 8.41 (d, J = 4.4 Hz, 1H), 8.63 (s, 1H), 8.75 (s, 1H), 8.90 (d, J = 4.4 Hz, 1H), 8.94 (s, 1H), 9.08 (s, 1H), 9.83 (s, 1H); LD-MS obsd 614.0; FAB-MS obsd 615.0759, calcd 615.0753 [(M + H)$^+$, M = $C_{31}H_{28}Br_2N_2$]; λ_{abs} 399, 413, 504, 651 nm.

II. General Procedure for the Palladium-Catalyzed Carbonylation. Unless noted otherwise, all palladium-catalyzed carbonylation reactions were carried out following the general procedure described below. The solid materials were placed in a Schlenk flask, and the flask was capped with a septum. The flask was evacuated, purged with argon (3 times), and subsequently evacuated and purged with carbon monoxide (3 times). The solvent was purged with argon (∼30 min) and subsequently with carbon monoxide (∼30 min). The required amount of solvent was then transferred via syringe to the reaction flask, following by any required liquid reagents. The reaction flask was placed in a preheated oil bath. For the reactions of duration less than ∼2 h, a slow flow of carbon monoxide was maintained by a long needle (the end of which was placed ∼2−3 mm above the solvent level) and a vented needle was also provided. For reactions of longer duration, a balloon of carbon monoxide was attached in a similar manner but without a vented needle.

The workup procedure and purification entailed chromatography. In some cases the crude reaction mixture showed trace amounts of palladium-chelated chlorin (upon LD-MS analysis), which could be separated from the free base chlorin target compound as a fast-running component upon chromatography. In each case where a chlorin−imide and chlorin−isoimide were observed, the former eluted prior to the latter.

Caution: Carbon monoxide is toxic. All handling of carbon monoxide should be carried out in a well-vented fume hood. Use of carbon monoxide sensors in the laboratory workspace is advised.

17,18-Dihydro-10-mesityl-13-methoxycarbonyl-18,18-dimethylporphyrin (FbC-M^{10}Es^{13}). Samples of **FbC-M^{10}Br^{13}** (41.0 mg, 0.0763 mmol) and $Pd(PPh_3)_4$ (88.1 mg, 0.0763 mmol) were reacted in toluene/DMF [7.6 mL, (1:1)] for 2 h at 80 °C under an atmosphere of CO as described in the General Procedure. A sample of MeONa (0.14 mL, 30% in MeOH, ∼10 equiv) was added. The resulting deep-green mixture was allowed to cool to room temperature and poured into saturated aqueous NH_4Cl. The resulting purple-brown mixture was extracted with CH_2Cl_2. The organic extract was washed (water and brine), dried (Na_2SO_4), and concentrated. Column chromatography afforded a trace of des-bromo chlorin (**FbC-M^{10}**, first fraction, green) and the title compound (second fraction, violet-purple) as a violet solid (26.1 mg, 66%): ^{1}H NMR δ −1.48 (br s, 1H), −1.18 (br s, 1H), 1.88 (s, 6H), 2.05 (s, 6H), 2.64 (s, 3H), 4.24 (s, 3H), 4.63 (s, 2H), 7.28 (s, 2H), 8.43 (d, J = 4.4 Hz, 1H), 8.76 (d, J = 4.4 Hz, 1H, partially overlapped), 8.77 (s, 1H, overlapped), 8.87 (d, J = 4.7 Hz, 1H), 9.08 (s, 1H), 9.11 (d, J = 4.7 Hz, 1H), 9.59 (s, 1H), 10.02 (s, 1H); ^{13}C NMR (75 MHz) δ 21.5, 31.1, 46.9, 51.9, 52.2, 94.6, 96.6, 106.3, 121.6, 123.5, 125.3, 128.0, 129.5, 129.7, 130.9, 132.7, 136.5, 137.6, 137.8, 138.0, 139.2, 142.8, 152.5, 153.8, 163.8, 166.4, 178.0; LD-MS obsd 516.3; ESI-MS obsd 517.2593, calcd 517.2598 [(M + H)$^+$, M = $C_{33}H_{32}N_4O_2$]; λ_{abs} 367, 405, 508, 653 nm.

17,18-Dihydro-10-mesityl-3,13-bis(methoxycarbonyl)-18,18-dimethylporphyrin (FbC-M^{10}Es^{3,13}). Samples of **FbC-M^{10}Br^{3,13}** (123 mg, 0.200 mmol) and $Pd(PPh_3)_4$ (463 mg, 0.400 mmol) were reacted in DMF/toluene [20 mL, (1:1)] at 80 °C for 2 h under an atmosphere of CO as described in the General Procedure. After 2 h, excess NaOMe (216 mg, 4.00 mmol) in MeOH (10 mL) was added to the reaction mixture. The latter was stirred at 80 °C for 5 min before being cooled to room temperature. A saturated aqueous solution of NH_4Cl (100 mL) was added, and the mixture was extracted with CH_2Cl_2. The organic layer was separated, filtered through Celite (CH_2Cl_2), and concentrated. Column chromatography [silica, hexanes/CH_2Cl_2 (1:2)] afforded a purple solid (95 mg,

83%): ^{1}H NMR δ −1.47 (br s, 2H), 1.84 (s, 6H), 2.04 (s, 6H), 2.62 (s, 3H), 4.22 (s, 3H), 4.35 (s, 3H), 4.63 (s, 2H), 7.24 (s, 2H), 8.40 (d, J = 4.4 Hz, 1H), 8.85 (s, 1H), 8.90 (d, J = 4.4 Hz, 1H), 9.10 (s, 1H), 9.43 (s, 1H), 10.04 (s, 1H), 10.61 (s, 1H); ESI-MS obsd 575.2653, calcd 575.2653 [$(M + H)^+$, M = $C_{35}H_{34}N_4O_4$]; λ_{abs} (CH_2Cl_2) 379, 413, 518, 550, 618, 675 nm.

15-Bromo-17,18-dihydro-10-mesityl-13-methoxycarbonyl-18,18-dimethylporphyrin (FbC-M^{10}Es^{13}Br^{15}). A solution of **FbC-M^{10}Es^{13}** (29.9 mg, 0.0579 mmol) in CH_2Cl_2/TFA [29 mL, (10:1)] was treated with NBS (0.580 mL, 0.10 M in CH_2Cl_2, 0.058 mmol). The deep-green mixture was stirred at room temperature for 30 min. Saturated aqueous $NaHCO_3$ was slowly added, and the resulting mixture was stirred for 5 min. The organic layer was separated, washed (water, brine), dried (Na_2SO_4), and concentrated. Column chromatography [silica, hexanes/CH_2Cl_2, (1:1)] afforded small amounts of unidentified chlorins (first fraction, pink; second fraction, purple) and the product (third fraction, purple), which upon concentration afforded a purple solid (27.0 mg, 78%): ^{1}H NMR δ −1.40 (br s, 2H), 1.84 (s, 6H), 2.03 (s, 6H), 2.61 (s, 3H), 4.20 (s, 3H), 4.58 (s, 2H), 7.23 (s, 2H), 8.39 (d, J = 4.4 Hz, 1H), 8.64 (s, 1H), 8.71 (s, 1H, overlapped), 8.72 (d, J = 4.4 Hz, 1H, partially overlapped), 8.84 (d, J = 4.8 Hz, 1H), 9.08 (d, J = 4.8 Hz, 1H), 9.52 (s, 1H); LD-MS obsd 594.9, ESI-MS obsd 595.1706, calcd 595.1703 [$(M + H)^+$, M = $C_{33}H_{31}BrN_4O_2$); λ_{abs} 365, 405, 509, 535, 598, 649 nm.

15-Bromo-17,18-dihydro-10-mesityl-3,13-bis(methoxycarbonyl)-18,18-dimethylporphyrin (FbC-M^{10}Es^{3,13}Br^{15}). A solution of **FbC-M^{10}Es^{3,13}** (100 mg, 0.174 mmol) in CH_2Cl_2/TFA [70 mL, (10:1)] was treated with NBS (1.74 mL, 0.10 M in CH_2Cl_2, 0.174 mmol). The deep-green solution was stirred at room temperature for 1 h. Saturated aqueous $NaHCO_3$ was slowly added, and the resulting mixture was stirred for 5 min. The organic layer was separated, dried (Na_2SO_4), and concentrated. Column chromatography (silica, CH_2Cl_2) afforded a purple solid (83 mg, 72%): ^{1}H NMR δ −1.55 (br s, 2 H), 1.82 (s, 6 H), 2.03 (s, 6 H), 2.59 (s, 3 H), 4.20 (s, 3 H), 4.33 (s, 3 H), 4.60 (s, 2 H), 7.23 (s, 2 H), 8.39 (d, J = 4.4 Hz, 1 H), 8.70 (s, 1 H), 8.81 (s, 1 H), 8.86 (d, J = 4.4 Hz, 1 H), 9.41 (s, 1 H), 10.53 (s, 1 H); ESI-MS obsd 653.1761, calcd 653.1763 [$(M + H)^+$, M = $C_{35}H_{33}BrN_4O_4$]; λ_{abs} (CH_2Cl_2) 378, 414, 520, 551, 615, 671 nm.

17,18-Dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboxylic Anhydride (FbC-M^{10}An). Samples of **FbC-M^{10}Es^{13}Br^{15}** (16.4 mg, 0.0275 mmol) and $Pd(PPh_3)_4$ (3.6 mg, 0.017 mmol) in DMF/toluene [2.75 mL, (1:1)] were reacted at 70 °C for 2 h under an atmosphere of CO as described in the General Procedure. After 2 h, a 2 M aqueous solution of NaOMe (120 μL) was added to the reaction mixture. The latter was stirred at 70 °C for 30 min before being allowed to cool to room temperature. Saturated aqueous NH_4Cl was added, and the mixture was extracted with CH_2Cl_2. The organic layer was separated, filtered through Celite (CH_2Cl_2), and concentrated. Column chromatography (silica, CH_2Cl_2) gave four fractions; the first fraction consisted of debrominated starting material, the second and third fractions contained unidentified chlorins, and the fourth fraction afforded the title compound as a purple solid (3.1 mg, 21%): ^{1}H NMR δ 0.19 (br s, 1H), 0.76 (br s, 1H), 1.86 (s, 6H), 1.98 (s, 6H), 2.58 (s, 3H), 4.80 (s, 2H), 7.22 (s, 2H), 8.21−8.32 (m, 1H), 8.53 (d, J = 6.33 Hz, 2H), 8.65−8.74 (m, 1H), 8.92−9.02 (m, 2H), 9.32 (s, 1H); LD-MS obsd 528.3; ESI-MS obsd 529.2242; calcd 529.2234 [$(M + H)^+$, M = $C_{33}H_{28}N_4O_3$]; λ_{abs} 414, 549, 680 nm. The same compound was prepared upon reaction of **FbC-M^{10}Es^{13}Br^{15}** (24.5 mg, 0.0411 mmol), $Pd(PPh_3)_4$ (47.5 mg, 0.0411 mmol), Cs_2CO_3 (39.8 mg, 0.124 mmol), and H_2O (1.4 μL, 0.078 mmol) in THF (5.0 mL) at 80 °C for 16 h under an atmosphere of CO as described in the General Procedure. The reaction mixture was filtered through Celite (CH_2Cl_2) and concentrated. Column chromatography (silica, CH_2Cl_2) provided debrominated starting material (first fraction) and the title compound (second fraction, 2.1 mg, 10%). Characterization data (^{1}H NMR, absorption, LD-MS) were consistent with those reported above.

13,15-Bis(methoxycarbonyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}Es^{13,15}). Samples of **FbC-M^{10}Es^{13}Br^{15}** (16 mg, 0.026 mmol), $Pd(PPh_3)_4$ (6.1 mg, 5.3 μmol), and K_2CO_3 (36 mg, 0.011 mmol) in THF/MeOH [1.6 mL, (1:1)] were reacted under an atmosphere of CO for 24 h at 85 °C as described in the General Procedure. The reaction mixture was filtered through Celite (CH_2Cl_2) and concentrated. Column chromatography [silica, hexanes/CH_2Cl_2 (3:1 to 1:2)] provided starting material, debrominated starting material (**FbC-M^{10}Es^{13}**), and the title product (purple fraction), which upon concentration afforded a purple solid (11 mg, 73%): ^{1}H NMR δ −0.67 (br s, 2H), 1.84 (s, 6H), 1.98 (s, 6H), 2.60 (s, 3H), 4.12 (s, 3H), 4.15 (s, 3H), 4.67 (s, 2H), 7.22 (s, 2H), 8.28 (d, J = 4.5 Hz, 1H), 8.62 (m, 2H), 8.75 (m, 2H), 9.00 (d, J = 4.8 Hz, 1H), 9.41 (s, 1H); LD-MS obsd 574.5; FAB-MS obsd 575.26528, calcd 575.26583 [$(M + H)^+$, M = $C_{35}H_{34}N_4O_4$]; λ_{abs} 361, 404, 506, 535, 602, 654 nm.

17,18-Dihydro-10-mesityl-18,18-dimethyl-13-[2-(*N*-propylamino)-1,2-dioxoethyl]porphyrin (FbC-M^{10}(COCmPr)^{13}). Samples of **FbC-M^{10}Br^{13}** (25 mg, 0.046 mmol) and $Pd(PPh_3)_4$ (54 mg, 0.046 mmol) were reacted in toluene/DMF [3 mL, (1:1)] for 3 h at 100 °C under an atmosphere of CO as described in the General Procedure. The reaction mixture was cooled to ∼60 °C, whereupon excess propylamine (0.50 mL) was added. Upon cooling to room temperature, the green-brown mixture was diluted with CH_2Cl_2, filtered through Celite (CH_2Cl_2), and concentrated. Column chromatography (silica, CH_2Cl_2) afforded a green solid (10 mg, 38%): ^{1}H NMR δ −0.89 (br s, 1H), −0.54 (br s, 1H), 1.08 (t, J = 7.4 Hz, 3H), 1.73−1.80 (m, 2H), 1.87 (s, 6H), 2.01 (s, 6H), 2.59 (s, 3H), 3.50 (app q, J = 6.8 Hz, 2H), 4.54 (s, 2H), 7.21 (s, 2H), 7.71 (app t, J = 5.8 Hz, 1H), 8.33 (d, J = 4.4 Hz, 1H), 8.63 (s, 1H), 8.66 (d, J = 4.4 Hz, 1H), 8.78 (d, J = 4.7 Hz, 1H), 9.02 (d, J = 4.7 Hz, 1H), 9.44 (s, 1H), 9.87 (s, 1H), 9.93 (s, 1H); ^{13}C NMR δ 11.5, 21.3, 21.5, 22.8, 30.7, 41.3, 46.6, 51.6, 94.3, 96.7, 106.3, 123.2, 125.3, 125.5, 127.9, 129.8, 131.2, 132.5, 133.1, 133.6, 136.8, 136.9, 152.6, 154.4, 162.4, 164.7, 178.8, 184.7; LD-MS obsd 571.2; ESI-MS obsd 572.3020, calcd 572.3020 [$(M + H)^+$, M = $C_{36}H_{37}N_5O_2$]; λ_{abs} 347, 376, 427, 518, 553, 615, 671 nm.

13-(*N*-Benzylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}(CmBn)^{13}). Samples of **FbC-M^{10}Br^{13}** (40.0 mg, 0.0744 mmol), $Pd(OAc)_2$ (2.5 mg, 0.011 mmol), Xantphos (6.5 mg, 0.011 mmol), Cs_2CO_3 (72.7 mg, 0.223 mmol), and benzylamine (16 μL, 0.15 mmol) were reacted in toluene (3.0 mL) for 12 h at 80 °C under an atmosphere of CO as described in the General Procedure. The reaction mixture was concentrated and chromatographed (silica, CH_2Cl_2) to afford a green solid (37.1 mg, 84%): ^{1}H NMR δ −1.74 (br s, 1H), −1.44 (br s, 1H), 1.85 (s, 6H), 2.04 (s, 6H), 2.61 (s, 3H), 4.63 (s, 2H), 4.97 (d, J = 5.6 Hz, 2H), 7.04 (app t, J = 5.6 Hz, 1H), 7.25 (s, 2H), 7.34−7.38 (m, 1H), 7.42−7.46 (m, 2H), 7.60−7.62 (m, 2H), 8.40 (d, J = 4.3 Hz, 1H), 8.71 (s, 1H), 8.81 (d, J = 4.4 Hz, 1H), 8.83 (s, 1H), 8.91 (d, J = 4.7 Hz, 1H), 9.15 (d, J = 4.6 1H), 9.65 (s, 1H), 10.09 (s, 1H); ^{13}C NMR δ 21.5, 21.7, 31.2, 44.4, 46.6, 52.0, 94.8, 97.2, 106.3, 122.0, 124.3, 125.0, 126.1, 127.9, 128.0, 128.5, 129.1, 129.2, 131.0, 132.3, 132.9, 136.1, 137.4, 137.7, 138.0, 138.7, 139.3, 142.3, 152.5, 153.3, 163.7, 166.1, 177.4; LD-MS obsd 591.5; ESI-MS obsd 592.3064, calcd 592.3071 [$(M + H)^+$, M = $C_{39}H_{37}N_5O$]; λ_{abs} 368, 405, 416, 508, 535, 600, 654 nm.

13-(*N*-Phenylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}(CmPh)^{13}). Samples of **FbC-M^{10}Br^{13}** (40.0 mg, 0.0744 mmol), $Pd(OAc)_2$ (2.5 mg, 0.011 mmol), Xantphos (6.5 mg, 0.011 mmol), Et_3N (31 μL, 0.22 mmol), and aniline (14 μL, 0.15 mmol) in toluene (3 mL) were reacted for 20 h at 80 °C under an atmosphere of CO as described in the General Procedure. The reaction mixture was concentrated and chromatographed (silica, CH_2Cl_2) to afford a green solid (27.5 mg, 64%): ^{1}H NMR δ −1.67 (br s, 1H), −1.35 (br s, 1H), 1.88 (s, 6H),

2.04 (s, 6H), 2.63 (s, 3H), 4.60 (s, 2H), 7.23−7.25 (m, 1H, partially overlapped with $CHCl_3$ signal), 7.29 (s, 2H), 7.47−7.51 (m, 2H), 7.90 (app d, J = 8.0 Hz, 2H), 8.41 (s, 1H, partially overlapped), 8.42 (d, J = 4.4 Hz, 1H, partially overlapped), 8.80−8.82 (m, 3H, three overlapped signals), 8.99 (d, J = 4.8 Hz, 1H), 9.15 (d, J = 4.8 Hz, 1H), 9.6 (s, 1H), 10.0 (s, 1H); ^{13}C NMR (75 MHz) δ 21.6, 21.7, 31.1, 46.9, 51.9, 94.8, 97.0, 106.3, 120.8, 122.3, 124.2, 124.8, 125.2, 126.3, 128.1, 129.4, 131.0, 132.5, 133.0, 136.4, 137.4, 137.7, 138.1, 138.4, 139.4, 142.5, 152.6, 153.6, 163.8, 164.4, 177.7 (signal of one carbon is not visible); LD-MS obsd 577.7; ESI-MS obsd 578.2912, calcd 578.2914 [$(M+H)^+$, M = $C_{38}H_{35}N_5O$]; λ_{abs} 368, 405, 416, 508, 535, 600, 654 nm.

3,13-Bis(*N*-benzylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}(CmBn)^{3,13}). Samples of **FbC-M^{10}Br^{3,13}** (32.9 mg, 0.0533 mmol), $Pd(OAc)_2$ (3.6 mg, 0.017 mmol), Xantphos (9.2 mg, 0.016 mmol), benzylamine (24 μL, 0.21 mmol), and Cs_2CO_3 (52.1 mg, 0.160 mmol) in toluene (2.1 mL) were reacted at 80 °C for 14 h under an atmosphere of CO as described in the General Procedure. The pink reaction mixture was concentrated under high vacuum, and the resulting solid was dissolved in CH_2Cl_2 and poured on a short silica column (CH_2Cl_2). Column chromatography [silica, hexanes/CH_2Cl_2/ethyl acetate (5:10:1)] afforded a pink solid (20.9 mg, 54%): ^{1}H NMR δ −1.42 (br s, 2H), 1.82 (s, 6H), 2.01 (s, 6H), 2.60 (s, 3H), 4.61 (s, 2H), 4.96 (d, J = 5.8 Hz, 2H), 5.07 (d, J = 5.7 Hz, 2H), 6.99−7.02 (m, 1H), 7.19−7.15 (m, 1H), 7.24 (s, 2H), 7.34−7.50 (m, 6H), 7.58−7.66 (m, 4H), 8.35 (d, J = 4.4 Hz, 1H), 8.70 (s, 1H), 8.79 (s, 1H), 8.88 (d, J = 4.4 Hz, 1H), 9.07 (s, 1H), 10.06 (s, 1H), 10.62 (s, 1H); LD-MS obsd 724.9; ESI-MS obsd 725.3587, calcd 725.3599 [$(M+H)^+$, M = $C_{47}H_{44}N_6O_2$]; λ_{abs} 375, 410, 515, 545, 613, 669 nm. The same compound was prepared upon replacement of Cs_2CO_3 with Et_3N: Samples of **FbC-M^{10}Br^{3,13}** (61.6 mg, 0.100 mmol), $Pd(OAc)_2$ (6.7 mg, 0.033 mmol), Xantphos (17.3 mg, 0.033 mmol), benzylamine (44 μL, 0.40 mmol), and Et_3N (84 μL, 0.60 mmol) in toluene (4 mL) were reacted under an atmosphere of CO at 80 °C for 3 h, affording upon analogous workup a pink-purple solid (41.8 mg, 58%). Characterization data (^{1}H NMR, absorption, LD-MS, ESI-MS) were consistent with those reported above.

3,13-Bis(*N*-phenylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}(CmPh)^{3,13}). Samples of **FbC-M^{10}Br^{3,13}** (100. mg, 0.162 mmol), $Pd(OAc)_2$ (11.1 mg, 0.0487 mmol), Xantphos (28.3 mg, 0.0487 mmol), Cs_2CO_3 (316 mg, 0.973 mmol), and aniline (60 μL, 0.65 mmol) were reacted in DMF/toluene [6.6 mL, (1:1)] for 20 h at 80 °C under an atmosphere of CO as described in the General Procedure. The reaction mixture was filtered through Celite (ethyl acetate) and concentrated. Column chromatography on a short silica column (CH_2Cl_2) afforded a red-brown solid (50 mg, 44%): ^{1}H NMR δ −1.48 (br s, 2H), 1.87 (s, 6H), 2.00 (s, 6H), 2.62 (s, 3H), 4.58 (s, 2H), 7.18−7.25 (m, 1H), 7.28 (s, 2H), 7.27−7.33 (m, 1H), 7.46−7.55 (m, 4H), 7.90 (d, J = 7.7 Hz, 2H), 7.98 (d, J = 7.7 Hz, 2H), 8.38 (d, J = 4.4 Hz, 1H), 8.42 (s, 1H), 8.66 (s, 1H), 8.83 (s, 1H), 8.86 (s, 1H), 8.89 (d, J = 4.40 Hz, 1H), 9.21 (s, 1H), 10.02 (s, 1H), 10.61 (s, 1H); ESI-MS obsd 697.3283, calcd 697.3286 [$(M+H)^+$, M = $C_{45}H_{40}N_6O_2$]; λ_{abs} (CH_2Cl_2) 412, 515, 548, 615, 671 nm.

13-(*N*-Benzylcarbamoyl)-15-bromo-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}(CmBn)^{13}Br^{15}). A solution of **FbC-M^{10}(CmBn)^{13}** (30.5 mg, 0.0515 mmol) in CH_2Cl_2/TFA [20.6 mL, (10:1)] was treated with NBS (0.52 mL, 0.10 M in CH_2Cl_2, 0.052 mmol). The deep-green solution was stirred at room temperature for 1 h. Saturated aqueous $NaHCO_3$ was slowly added, and the resulting mixture was stirred for 5 min. The organic layer was separated, dried (Na_2SO_4), and concentrated. Column chromatography (silica, CH_2Cl_2) provided an unidentified first fraction (pink), starting material (second fraction), an unidentified fraction (third, pink), and the title compound (purple fraction); concentration of the latter afforded a purple solid (24.5 mg, 71%): ^{1}H NMR δ −1.60 (br s, 2H), 1.83 (s, 6H), 2.03 (s, 6H), 2.62 (s, 3H), 4.60 (s, 2H), 4.92 (d, J = 5.4 Hz, 2H), 6.59 (t, J = 5.4 Hz, 1H), 7.24 (s, 2H), 7.31−7.36 (m, 1H), 7.39−7.43 (m, 2H), 7.56−7.58 (m, 2H), 8.40−8.41 (m, 1H), 8.64 (s, 1H), 8.74−8.76 (m, 1H, partially overlapped), 8.76 (s, 1H, partially overlapped), 8.87 (d, J = 4.7 Hz, 1H), 9.11 (d, J = 4.7 Hz, 1H), 9.57 (s, 1H) (signal of one N−H proton is not visible); LD-MS obsd 590.5 $(M-Br)^+$; ESI-MS obsd 670.2166, calcd 670.2176 [$(M+H)^+$, M = $C_{39}H_{36}BrN_5O$]; λ_{abs} 364, 405, 509, 534, 596, 648 nm.

15-Bromo-13-(*N*-phenylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}(CmPh)^{13}Br^{15}). A solution of **FbC-M^{10}(CmPh)^{13}** (27.0 mg, 0.0467 mmol) in CH_2Cl_2/TFA [18.6 mL, (10:1)] was treated with NBS (0.47 mL, 0.10 M in CH_2Cl_2, 0.047 mmol). The deep-green reaction mixture was stirred at room temperature for 45 min. Saturated aqueous $NaHCO_3$ was slowly added, and the resulting mixture was vigorously stirred for 5 min. The organic layer was separated, washed (water, brine), dried (Na_2SO_4), and concentrated. Column chromatography [silica, hexanes/CH_2Cl_2 (1:3)] gave four fractions; the first purple fraction was an unidentified chlorin, the second greenish fraction was unreacted starting material, the third fraction was an unidentified chlorin, and the fourth fraction afforded the title compound as a purple solid (18.7 mg, 61%): ^{1}H NMR δ −1.51 (br s, 2H), 1.84 (s, 6H), 2.04 (s, 6H), 2.59 (s, 3H), 4.59 (s, 2H), 7.21−7.24 (m, 1H, partially overlapped), 7.22 (s, 2H), 7.44−7.48 (m 2H), 7.84 (app d, J = 7.7 Hz, 2H), 7.99 (s, 1H), 8.41 (d, J = 4.4 Hz, 1H); 8.70 (s, 1H), 8.75 (d, J = 4.4 Hz, partially overlapped), 8.76 (s, 1H), 8.90 (d, J = 4.4 Hz, 1H), 9.12 (d, J = 4.4 Hz, 1H), 9.57 (s, 1H); ESI-MS obsd 656.2015, calcd 656.2025 [$(M+H)^+$, M = $C_{38}H_{34}BrN_5O$]; λ_{abs} 365, 405, 509, 534, 596, 649 nm.

15-Bromo-3,13-bis(*N*-benzylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}(CmBn)^{3,13}Br^{15}). A solution of **FbC-M^{10}(CmBn)^{3,13}** (20.5 mg, 0.0283 mmol) in CH_2Cl_2/TFA [11.3 mL, (10:1)] was treated with NBS (0.283 mL, 0.10 M in CH_2Cl_2, 0.028 mmol). The resulting deep-green mixture was stirred at room temperature for 40 min, whereupon another batch of NBS (0.056 mL, 0.0056 mmol) was added, and the reaction mixture was stirred for an additional 30 min. Saturated aqueous $NaHCO_3$ was added slowly, and the resulting mixture was stirred vigorously for 5 min. The organic layer was separated, washed (water and brine), dried (Na_2SO_4), and concentrated. The resulting purple solid was dissolved in CH_2Cl_2 (with the aid of sonication) and chromatographed [silica, hexanes/CH_2Cl_2/ethyl acetate (5:10:1)] to afford traces of unknown substances, unreacted starting material (highly fluorescent, purple fraction), and the expected product; concentration of the latter afforded a violet solid (16.2 mg, 71%): ^{1}H NMR δ −1.65 (br s, 1H), 1.80 (s, 6H), 1.88 (s, 6H), 2.60 (s, 3H), 4.49 (s, 2H), 4.91 (d, J = 5.6 Hz, 2H), 5.05 (d, J = 5.6 Hz, 2H), 6.59 (t, J = 5.6 Hz, 1H), 7.23 (s, 2H), 7.26 (1H, overlapped with $CHCl_3$ signal), 7.34−7.48 (m, 6H), 7.56−7.64 (m, 4H), 8.36 (d, J = 4.4 Hz, 1H), 8.62 (s, 1H), 8.65 (s, 1H), 8.83 (d, J = 4.4 Hz, 1H), 9.05 (s, 1H), 10.56 (s, 1H) (signal of one N−H proton is not visible); LD-MS obsd 723.4 $(M-Br)^+$; ESI-MS obsd 803.2698, calcd 803.2704 [$(M+H)^+$, M = $C_{47}H_{43}BrN_6O_2$]; λ_{abs} 374, 411, 517, 547, 611, 666 nm.

15-Bromo-3,13-bis(*N*-phenylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin (FbC-M^{10}(CmPh)^{3,13}Br^{15}). A solution of **FbC-M^{10}(CmPh)^{3,13}** (50 mg, 0.072 mmol) in CH_2Cl_2/TFA [30 mL, (10:1)] was treated with NBS (0.72 mL, 0.10 M in CH_2Cl_2, 0.072 mmol). The deep-green solution was stirred at room temperature for 1 h. Saturated aqueous $NaHCO_3$ was slowly added, and the resulting mixture was stirred for 5 min. The organic layer was separated, dried (Na_2SO_4), and concentrated. Column chromatography on a short silica column

(CH_2Cl_2) afforded a red-brown solid (41 mg, 74%): ^{1}H NMR δ −1.55 (br s, 2H), 1.84 (s, 6H), 1.98 (s, 6H), 2.59 (s, 3H), 4.56 (s, 2H), 7.23 (s, 2H), 7.29−7.34 (m, 2H), 7.48 (t, J = 7.8 Hz, 2H), 7.55 (t, J = 7.8 Hz, 2H), 7.85 (d, J = 7.7 Hz, 2H), 7.98 (d, J = 7.7 Hz, 2H), 8.02 (s, 1H), 8.39 (d, J = 4.4 Hz, 1H), 8.64 (s, 1H), 8.75 (s, 1H), 8.77 (s, 1H), 8.85 (d, J = 4.4 Hz, 1H), 9.20 (s, 1H), 10.55 (s, 1H); ESI-MS obsd 775.2393, calcd 775.2391 [$(M+H)^+$, M = $C_{45}H_{39}BrN_6O_2$]; λ_{abs} (CH_2Cl_2) 412, 518, 549, 614, 668 nm.

13^2-*N*-Benzyl-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboximide (FbC-M^{10}I-Bn). Samples of **FbC-M^{10}(CmBn)^{13}Br^{15}** (15.2 mg, 0.0226 mmol) and $Pd(PPh_3)_4$ (26.1 mg, 0.0226 mmol) were reacted in toluene/DMF [1.5 mL, (1:1)] at 80 °C for 2 h under an atmosphere of CO as described in the General Procedure. The flow of CO was then stopped, and the reaction mixture was kept at 80 °C for 1 h. The reaction mixture was filtered through Celite (CH_2Cl_2) and concentrated. Column chromatography (silica, CH_2Cl_2) provided the title compound (first fraction, purple) and debrominated starting material (second fraction, 6.5 mg). Data for the title compound: purple solid (7 mg, 50%): ^{1}H NMR δ 0.08 (br s, 1H), 0.43 (br s, 1H), 1.86 (s, 6H), 1.95 (s, 6H), 2.58 (s, 3H), 4.82 (s, 2H), 5.67 (s, 2H), 7.20 (s, 2H), 7.24−7.28 (m, 1H, partially overlapped with residual $CHCl_3$), 7.34−7.39 (m, 2H), 7.74−7.76 (m, 2H), 8.26 (d, J = 4.4 Hz, 1H), 8.53 (s, 1H), 8.53 (d, partially overlapped with singlet), 8.66 (d, J = 4.8 Hz, 1H), 8.94 (d, J = 4.8 Hz, 1H), 8.99 (s, 1H), 9.32 (s, 1H); ^{13}C NMR (75 MHz) δ 21.4, 21.6, 31.5, 46.4, 51.4, 54.0, 93.7, 96.1, 110.2, 119.7, 123.9, 125.9, 127.1, 128.3, 128.5, 128.7, 128.8, 131.1, 133.2, 133.7, 136.6, 137.1, 138.4, 138.6, 138.7, 140.3, 144.5, 147.3, 153.2, 154.2, 164.5, 171.9, 180.9; LD-MS obsd 618.0; ESI-MS obsd 618.2866, calcd 618.2864 [$(M + H)^+$, M = $C_{40}H_{35}N_5O_2$]; λ_{abs} 363, 420, 553, 686 nm.

13^1-*N*-Benzylimino-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboxisoimide (FbC-M^{10}Iso-Bn). Samples of **FbC-M^{10}(CmBn)^{13}Br^{15}** (24.3 mg, 0.0362 mmol), $Pd(PPh_3)_4$ (41.8 mg, 0.0362 mmol), and Cs_2CO_3 (35.7 mg, 0.109 mmol) were reacted in toluene (1.5 mL) at 80 °C for 2 h under an atmosphere of CO as described in the General Procedure. The resulting mixture was diluted with CH_2Cl_2, filtered through Celite, and concentrated. Column chromatography (silica, CH_2Cl_2) afforded a trace of **FbC-M^{10}I-Bn** (first fraction, purple) and the title compound (second fraction, purple), which upon concentration afforded a purple solid (12.2 mg, 55%): ^{1}H NMR δ − 0.55 (br s, 1H), − 0.12 (br s, 1H), 1.84 (s, 6H), 2.02 (s, 6H), 2.57 (s, 3H), 4.92 (s, 2H), 5.24 (s, 2H), 7.20 (s, 2H), 7.30−7.33 (m, 1H), 7.40−7.45 (m, 2H), 7.64−7.67 (m, 2H), 8.30 (d, J = 4.4 Hz, 1H), 8.65 (d, J = 4.4 Hz, 1H), 8.70 (s, 1H), 8.77 (d, J = 4.8 Hz, 1H), 9.04 (s, 1H), 9.06 (d, J = 4.8 Hz, 1H), 9.51 (s, 1H); ^{13}C NMR (75 MHz) δ 21.1, 21.4, 31.3, 46.2, 51.2, 53.8, 53.5, 95.8, 110.0, 119.5, 123.7, 125.7, 126.9, 128.0, 128.3, 128.5, 128.6, 130.9, 132.9, 130.0, 133.5, 136.4, 136.9, 138.2, 138.35, 138.44, 140.1, 144.3, 147.0, 152.9, 153.9, 164.2, 171.7, 180.7; LD-MS obsd 617.8, 526.7 (M − Bn)$^+$; ESI-MS obsd 618.2857, calcd 618.2864 [$(M+H)^+$, M = $C_{40}H_{35}N_5O_2$]; λ_{abs} 363, 414, 507, 544, 625, 679 nm.

13^2-*N*-Phenyl-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboximide (FbC-M^{10}I-Ph). Samples of **FbC-M^{10}(CmPh)^{13}Br^{15}** (7.0 mg, 0.011 mmol), $Pd(PPh_3)_4$ (2.5 mg, 0.0022 mmol), and Cs_2CO_3 (10.7 mg, 0.033 mmol) were reacted in toluene (1 mL) at 80 °C for 14 h under an atmosphere of CO as described in the General Procedure. The reaction mixture was diluted with CH_2Cl_2, filtered through Celite, and chromatographed [silica, hexanes/CH_2Cl_2, (1:1 to 3:1)] to afford a trace of debrominated starting material (first fraction), unreacted starting material (second fraction), and the title compound (third fraction, 3 mg, 45%): ^{1}H NMR δ 0.15 (br s, 1H), 0.58 (br s, 1H), 1.88 (s, 6H), 1.93 (s, 6H), 2.58 (s, 3H), 4.79 (s, 2H), 7.21 (s, 2H), 7.56−7.58 (m, 3H), 7.63−7.68 (m, 2H), 8.26 (d, J = 4.4 Hz, 1H), 8.55 (d, J = 4.4 Hz, 1H), 8.55 (s, 1H, overlapped with doublet), 8.68 (d, J = 4.8 Hz, 1H), 8.97 (d, J = 4.8 Hz, 1H), 9.03 (s, 1H), 9.34 (s, 1H); LD-MS obsd 603.8; ESI-MS obsd 604.2712, calcd 604.2707 [$(M+H)^+$, M = $C_{39}H_{33}N_5O_2$]; λ_{abs} 364, 419, 551, 685 nm.

13^1-*N*-Phenylimino-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboxisoimide (FbC-M^{10}Iso-Ph). Samples of **FbC-M^{10}(CmPh)^{13}Br^{15}** (23.5 mg, 0.0358 mmol), $Pd(PPh_3)_4$ (41.3 mg, 0.0358 mg), and Cs_2CO_3 (35.0 mg, 0.107 mmol) were reacted in toluene (1.4 mL) at 80 °C for 2 h under an atmosphere of CO as described in the General Procedure. The resulting mixture was diluted with CH_2Cl_2, filtered through Celite, and concentrated. Column chromatography [silica, hexanes/CH_2Cl_2 (1:3)] afforded a purple solid (12.8 mg, 59%): ^{1}H NMR δ −0.41 (br s, 1H), 0.07 (br s, 1H); 1.90 (s, 6H), 2.00 (s, 6H), 2.59 (s, 3H), 4.87 (s, 2H), 7.24 (s, 2H), 7.23−7.24 (m, 1H, overlapped with singlet), 7.47−7.51 (m, 2H), 7.53−7.56 (m, 2H), 8.33 (d, J = 4.4 Hz, 1H), 8.65 (d, J = 4.4 Hz, 1H), 8.68 (s, 1H), 8.76 (d, J = 4.7 Hz, 1H), 9.05 (d, J = 4.7 Hz, 1H), 9.13 (s, 1H), 9.49 (s, 1H); ^{13}C NMR δ 21.1, 21.4, 31.2, 46.2, 53.7, 93.5, 95.9, 109.9, 119.3, 123.7, 124.1, 124.8, 126.0, 128.1, 128.6, 128.9, 131.1, 133.0, 133.2, 133.6, 136.3, 137.2, 138.3, 138.5, 144.7, 145.4, 145.7, 153.0, 154.3, 164.0, 172.0, 181.2 (signal of one carbon is not visible); ESI-MS obsd 604.2711, calcd 604.2707 [$(M+H)^+$, M = $C_{39}H_{33}N_5O_2$]; λ_{abs} 367, 418, 512, 550, 634, 687 nm.

13^2-*N*-Benzyl-3-(*N*-benzylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboximide (FbC-(CmBn)^{3}M^{10}I-Bn). Samples of **FbC-M^{10}(CmBn)^{3,13}Br^{15}** (20.5 mg, 0.0255 mmol), $Pd(PPh_3)_4$ (29.5 mg, 0.0255 mmol), and Cs_2CO_3 (25 mg, 0.077 mmol) were reacted in toluene (4.0 mL) at 80 °C for 20 h under an atmosphere of CO as described in the General Procedure. The reaction mixture was filtered through Celite (ethyl acetate) and concentrated. Column chromatography (silica, CH_2Cl_2) gave two fractions; the first fraction afforded the title compound as a purple solid (6.1 mg, 32%); the second fraction afforded the chlorin−isoimide **FbC-(CmBn)^{3}M^{10}Iso-Bn** as a purple solid (5.0 mg, 26%). Data for **FbC-(CmBn)^{3}M^{10}I-Bn**: ^{1}H NMR δ 0.11 (br s, 1H), 0.29 (br s, 1H), 1.85 (s, 6H), 1.92 (s, 6H), 2.58 (s, 3H), 4.82 (s, 2H), 5.01 (d, J = 5.8 Hz, 2H), 5.66 (s, 2H), 7.21 (s, 2H), 7.32−7.44 (m, 3H), 7.43−7.52 (m, 2H), 7.55−7.64 (m, 2H), 7.66−7.79 (m, 3H), 8.25 (d, J = 4.4 Hz, 1H), 8.53 (s, 1H), 8.65 (d, J = 4.7 Hz, 1H), 8.85 (s, 1H), 9.05 (s, 1H), 10.34 (s, 1H); ESI-MS obsd 751.3392, calcd 751.3391 [$(M+H)^+$, M = $C_{48}H_{42}N_6O_3$]; λ_{abs} 378, 424, 564, 708 nm. Data for **FbC-(CmBn)^{3}M^{10}Iso-Bn**: ^{1}H NMR δ −0.42 (br s, 1H), −0.14 (br s, 1H), 1.83 (s, 6H), 1.97 (s, 6H), 2.57 (s, 3H), 4.90 (s, 2H), 5.03 (d, J = 5.6 Hz, 2H), 5.23 (s, 2H), 7.20 (s, 2H), 7.43 (m, 5 H), 7.57−7.67 (m, 3H), 7.67−7.80 (m, 2H), 8.26 (d, J = 4.4 Hz, 1H), 8.66 (s, 1H), 8.74 (d, J = 4.4 Hz, 1H), 8.93 (s, 1H), 9.06 (s, 1H), 10.52 (s, 1H); ESI-MS obsd 751.3393, calcd 751.3391 [$(M+H)^+$, M = $C_{48}H_{42}N_6O_3$]; λ_{abs} 418, 555, 699 nm.

13^2-*N*-Phenyl-3-(*N*-phenylcarbamoyl)-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboximide (FbC-(CmPh)^{3}M^{10}I-Ph). Samples of **FbC-M^{10}(CmPh)^{3,13}Br^{15}** (10.0 mg, 0.0129 mmol), $Pd(PPh_3)_4$ (14.8 mg, 0.0129 mmol), and Cs_2CO_3 (12.6 mg, 0.0387 mmol) were reacted in toluene (2.0 mL) at 80 °C for 20 h under an atmosphere of CO as described in the General Procedure. The reaction mixture was filtered through Celite (ethyl acetate) and concentrated. Column chromatography on a short silica column (CH_2Cl_2) afforded a purple-green solid (6.7 mg, 72%): ^{1}H NMR δ 0.19 (br s, 1H), 0.42 (br s, 1H), 1.87 (s, 6H), 1.92 (s, 6H), 2.58 (s, 3H), 4.80 (s, 2H), 7.22 (s, 2H), 7.53 (m, 6H), 7.64 (d, J = 7.4 Hz, 2H), 7.93 (d, J = 7.7 Hz, 2H), 8.25 (d, J = 4.4 Hz, 1H), 8.55 (s, 1H), 8.60 (s, 1H), 8.66 (d, J = 4.7 Hz, 1H), 8.98 (s, 1H), 9.11 (s, 1H), 10.35 (s, 1H); ESI-MS obsd 723.3076, calcd 723.3078 [$(M + H)^+$, M = $C_{46}H_{38}N_6O_3$]; λ_{abs} (CH_2Cl_2) 422, 565, 660, 710 nm.

13^2-*N*-Benzyl-3-methoxycarbonyl-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboximide (FbC-Es^{3}M^{10}I-Bn). Samples of **FbC-M^{10}Es^{3,13}Br^{15}** (35.5 mg, 0.0543 mmol), $Pd(PPh_3)_4$ (63.0 mg,

0.0543 mmol), Cs_2CO_3 (54 mg, 0.16 mmol), and benzylamine (12 μL, 0.11 mmol) were reacted in THF (3.6 mL) at 80 °C for 20 h under an atmosphere of CO as described in the General Procedure. The reaction mixture was filtered through Celite (ethyl acetate) and concentrated. Column chromatography (silica, CH_2Cl_2) afforded a green solid (21 mg, 57%): ^{1}H NMR δ 0.19 (br s, 1H) (a signal for one NH proton was not visible), 1.85 (s, 6H), 1.95 (s, 6H), 2.58 (s, 3H), 4.32 (s, 3H), 4.84 (s, 2H), 5.67 (s, 2H), 7.21 (s, 2H), 7.34−7.39 (m, 3H), 7.74 (d, J = 6.9 Hz, 2H), 8.27 (d, J = 4.4 Hz, 1H), 8.63 (s, 1H), 8.69 (d, J = 4.4 Hz, 1H), 9.07 (s, 1H), 9.23 (s, 1H), 10.35 (s, 1H); ESI-MS obsd 676.2922, calcd 676.2918 [$(M + H)^+$, M = $C_{42}H_{37}N_5O_4$]; λ_{abs} (CH_2Cl_2) 379, 424, 568, 659, 715 nm.

Zn(II)-13^2-*N*-Phenyl-17,18-dihydro-10-mesityl-18,18-dimethylporphyrin-13,15-dicarboximide (ZnC-M^{10}I-Ph). A solution of **FbC-M^{10}I-Ph** (2.0 mg, 0.033 mmol) in CH_2Cl_2 (1.0 mL) was treated with 0.1 mL of methanolic $Zn(OAc)_2 \cdot 2H_2O$ (37 mg, 0.17 mmol), and the reaction mixture was stirred at room temperature for 16 h. Standard workup and chromatography (silica, CH_2Cl_2) gave the title compound (2 mg, 90%): ^{1}H NMR δ 1.89 (s, 6H), 1.89 (s, 6H), 2.56 (s, 3H), 4.73 (s, 2H), 7.18 (s, 2H), 7.45−7.57 (m, 3H), 7.58−7.67 (m, 2H), 8.13−8.20 (m, 1H), 8.23−8.29 (m, 1H), 8.44−8.52 (m, 2H), 8.78−8.88 (m, 1H), 8.96 (s, 1H), 9.12 (s, 1H); ESI-MS obsd 666.1849, calcd 666.1842 [$(M + H)^+$, M = $C_{39}H_{31}N_5O_2$]; λ_{abs} 425, 558, 615, 661 nm.

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Supporting Information Available: Spectral data (^{1}H NMR and ^{13}C NMR) for all new chlorins including spectral assignments; exploratory studies concerning routes to chlorin−imides; additional information concerning experimental procedures; X-ray data for **FbC-M^{10}Iso-Bn**, **FbC-M^{10}Iso-Ph**, and **ZnC-M^{10}I-Ph**. This material is available free of charge via the Internet at http://pubs.acs.org.