HETEROCYCLES, Vol 16, No 3, 1981

COVALENTLY LINKED DIMERIC PORPHYRINS

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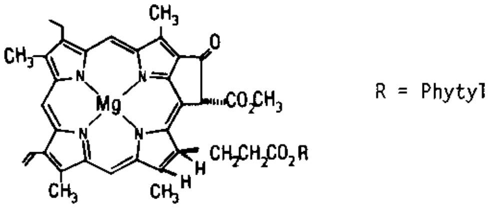
ABSTRACT

The synthesis, spectral properties and applications of singly and multiply covalently linked bis- and tris- porphyrins, chlorins and bacteriochlorins are reviewed.

The interactions between porphyrins and related tetrapyrrolic macrocycles play many varied and important biological functions. In photosynthesis the harvesting and transport of photons by antennae molecules, such as chlorophyll a (1), depends upon the close proximity of these molecules to each other. The final destination of the photons are the "special pairs" (P700, or P870 in bacteria) which are two macrocyclic tetrapyrroles serving as the electron donors of photosynthesis. These photochemically derived electrons, like those generated chemically during respiration are conducted through the cell by a series of heme proteins, the cytochromes, where once again the proximity and interaction of the porphyrin rings allow for the facile electron flow. In aerobic organisms the electrons are delivered to cytochrome oxidase which contains two heme moieties (cytochromes a, and a_3) which in concert with two copper ions control the four electron reduction of dioxygen to water.

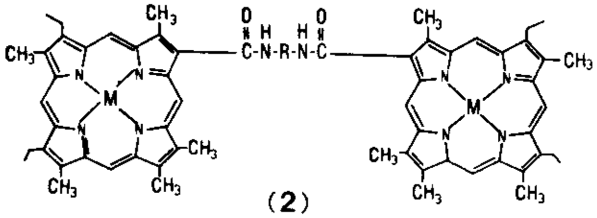


(1)

While in none of the above systems are the tetrapyrrolic macrocycles covalently linked, their proximity and relative orientations are of critical importance. In nature this spacing is in general achieved by orientation in membranes. As yet the bioorganic chemist is not sufficiently skilled to mimic these membranes. Instead the relative disposition of dimeric porphyrins have been controlled by linking them covalently. We describe here the synthetic approaches towards such systems and some properties exhibited by dimeric porphyrins.

Synthesis

We initiated[1] this area of research by covalently linking two porphyrins via an amide linkage to give porphyrins of type (2). 2-Carboxy-7,12-diethyl-3,8,13,17,18-pentamethylporphyrin was reacted with oxalyl chloride to give the acid chloride, which was treated with an excess of ethylenediamine or *p*-phenylenediamine to give 2-(2-aminoethylaminocarbonyl) or 2-(*p*-aminophenylaminocarbonyl) porphyrins. These were metallated with copper or cobalt and reacted with more of the acid chloride porphyrin to give a series of singly metallated bisporphyrins. Treatment with zinc acetate afforded the mixed metal bisporphyrins.



(2)

R = $-CH_2CH_2-$ or R = $-C_6H_4-$

While this method of covalent linkage is almost trivially easy, and despite the fact that others (vide infra) have followed the same path, the amide linkages (and esters or ethers also employed) present two major problems. Porphyrins and metalloporphyrins are inherently of low solubility and dimeric porphyrins even more so; and the incorporation of an amide linkage additionally decreases the solubility. Secondly, the amide linkage is a reasonably reactive functional group, and although amide linkages maintain their integrity under physiological conditions this is not necessarily the case in the laboratory. It has been our experience, and that of others, that such covalently linked dimeric porphyrins readily cleave to monomeric species. The only advantage other than convenience to such linkages is that mixed-metal dimers are most readily prepared by coupling of pre-metallated monomers.

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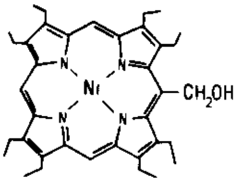
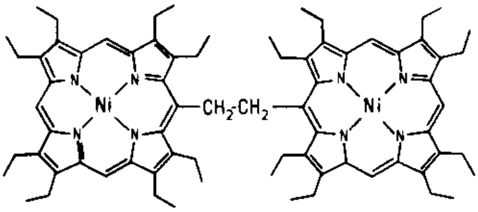
Many other researchers have since entered the field. Rather than present their work in simple chronological order, we shall divide the compounds involved into several related classes-singly linked versus multiply-linked (which have strikingly different geometries and physical properties) and within these classes (for the same reasons), β-octaalkyl versus meso-tetraaryl porphyrins, and porphyrins versus chlorins.

The first reported example (since ours) among the singly-linked octaalkyl porphyrins was the product of an accidental dimerization. Treatment of meso-hydroxymethyl octaethylporphinato nickel (**3**) with 50% sulfuric acid-dimethyl formamide resulted in meso,meso'- 1,2-ethylenebisoctaethylporphinato nickel (**4**) in 50% yield[2]. This was the first reported dimer linked solely through carbon. The synthesis, of course, is not amenable to linkages other than two-carbons long.



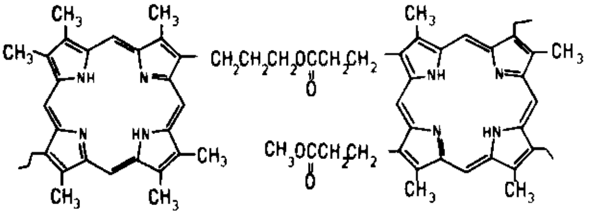
(**3**)



(**4**)

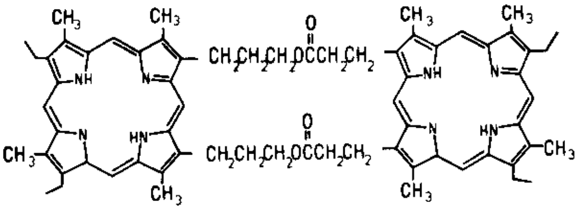
Whereas the preceding substance is a totally synthetic one, many researchers have found it convenient to employ the readily-available naturally-derived porphyrins such as protoporphyrin and its derivatives. Owing to the lability of the vinyl groups to photo-oxidize, they are usually hydrogenated to ethyls (mesoporphyrin) or cleaved off (deuteroporphyrin) before being applied to dimer work. Further, many have found it convenient to employ the mixtures of mono-esters available from the unselective mono-saponification of the diester (or mono-esterification of the diacid).

Ichimura[3] prepared a mixture of singly-linked porphyrins (one of which is shown as (**5**)) by reacting the acid chloride of the mixture of monomethyl esters of mesoporphyrin IX (derived from a partial saponification of the



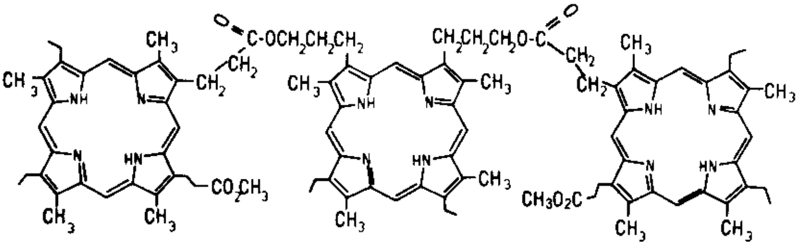
(5)

diester) with 2-(3-hydroxypropyl)-3,7,8,13,17,18-hexamethyl-12-propylporphyrin. Reaction of the diacid chloride of mesoporphyrin IX with 3,7-bis(3-hydroxypropyl)-2,8,13,18-tetramethyl-12,17-diethylporphyrin gave the doubly linked bisporphyrin (**6**) as an isomeric mixture. Reaction of the same bis(3-



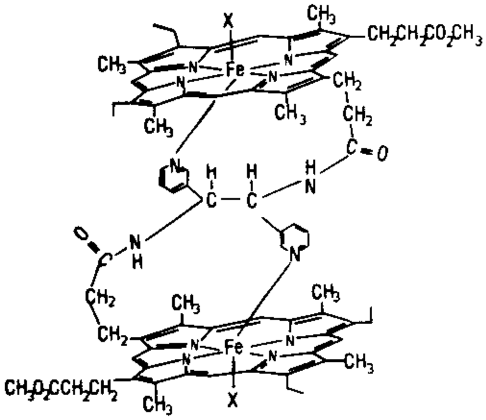
(6)

hydroxypropyl) porphyrin with 2 equivalents of the acid chloride of the monomethyl ester of mesoporphyrin IX gave a mixture of trimers (such as (**7**)).



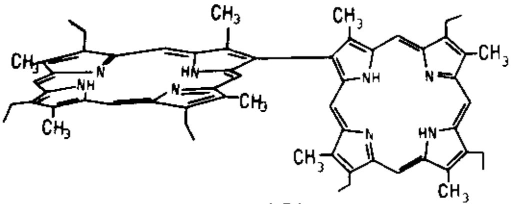
(7)

Traylor et al.[4] coupled meso-1,2-di(3-pyridyl)-ethylenediamine with the mixed mesoporphyrin IX monomethyl esters through the pivaloyl anhydride to give the bisporphyrin mixture. Insertion of iron gave the bisporphyrin ((**8**) etc.).



(8)

The use of amide or ester linkages had caused a decrease in solubility in these systems (which already had low solubility), thus in our own laboratories we took a different approach to the linking of octaalkyl porphyrins. The synthesis of a covalently linked bisporphyrin joined by an unbroken chain of carbon atoms (of variable length) was accomplished by constructing the link first and subsequently building a porphyrin at each end.[5] This has the advantage of allowing very short chains, i.e. β,β'-biporphyrin (**9**), and



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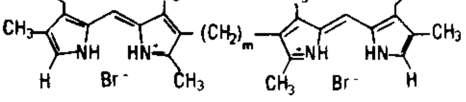
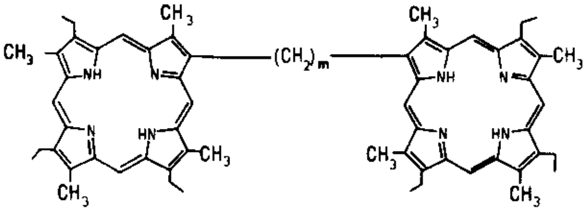
results in a greater stability of the link, i.e. no hydrolysis as in esters and amides. The porphyrins were formed from the linked bisdipyrromethenes



(10)

(**10**) under the conditions of the Johnson porphyrin synthesis (stannic chloride in dichloromethane followed by dimethyl sulfoxide, pyridine) to give the bisporphyrins (**11**).

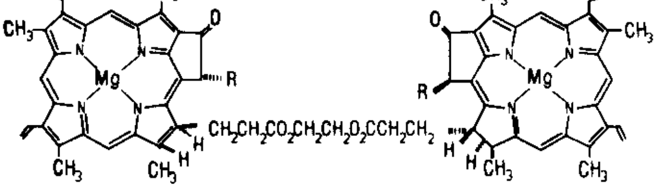


(11)

This synthesis is amenable to branched chains, even functionalized ones, as well as linear. The β,β'-biporphyrin was the first reported example of directly linked porphyrin dimers; we have since managed to synthesize a meso-β'-biporphyrin in low yield[6] from an α,β'-dipyrrylmethane but to date, similar approaches to a meso,meso'- biporphyrin (from a 1,2-bis-2-pyrrolyl ethane) have proved fruitless. (The linkage is cleaved during the oxidation process.)

Not only porphyrins have been linked to form dimers, but chlorins as well, especially in attempts to mimic the proximity effects necessarily present among photosynthetic chlorins in vivo. Chlorophyll and its degradation products were the usual partners to such linkage, due to their ready availability. The degradation products were often chosen for reasons of enhanced stability towards oxidation or hydrolysis compared to the chlorophyllide esters, themselves.

Boxer and Closs,[7] working on P-700 models, in a hope of mimicking the chlorophyll "special pair", transesterified methyl pyropheophorbide a with ethylene glycol to afford the monoester. Treatment with pyropheophorbide a activated by 1,1'-carbonyldiimidazole resulted in the di-ester which was metallated with magnesium by the Eschenmoser method to give (**12**).

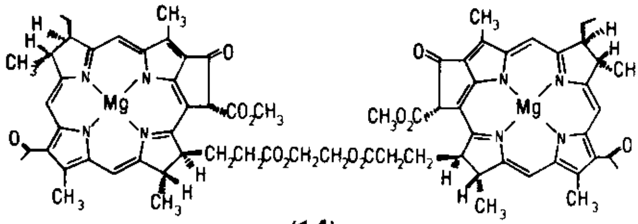


(12) R = -H

(13) R = $-CO_2CH_3$

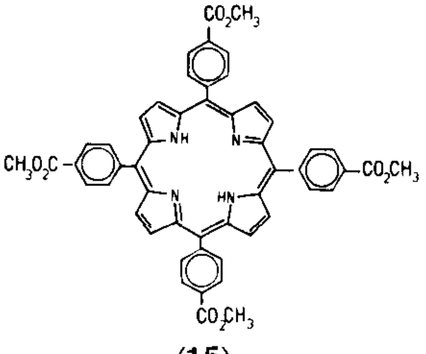
Wasielewski et al.[8] working in the same field treated pheophorbide a at room temperature in tetrahydrofuran/pyridine with methyl chloroformate and esterified the anhydride with excess ethylene glycol to give the monoester of pheophorbide a. Coupling was carried out in pyridine at 0° with a 2:1 molar ratio of the monoester to pheophorbide a using the mild acylating agent phosgene to give the dimer (**13**).

Wasielewski et al.[9] also produced the bacteriochlorophyll dimer (**14**) by the esterification of bacteriopheophorbide a with ethylene glycol using benzotriazole N-methanesulfonate and triethylamine in tetrahydrofuran to give the mono ester. This was coupled with a second bacteriopheophorbide by the same method except that 4-dimethylaminopyridine was used as the base and dichloromethane as solvent.



(14)

Less closely related to naturally occurring porphyrins in geometry, electronic configurations and properties, are the meso-tetraryl (and tetraalkyl) porphyrins. These substances owe their constant popularity (especially among the dilettantes of porphyrin chemistry) to their ease of synthesis-usually in one pot from pyrrole and a suitable aryl aldehyde or mixture, in refluxing propionic acid. Linkages have invariably been attached to the aryl meso-substituents. Use of aldehyde mixtures led to mixtures of porphyrins which could frequently be separated by column chromatography, and used after proper characterization. The first singly linked tetra-aryl porphyrin dimer of this sort was reported by Anton et al.[10], who transesterified 5,10,15,20-tetra-(4-carbomethoxyphenyl)porphyrin (**15**) with an equimolar quantity of ethylene glycol. The resultant six component mixture was separated by chromatography to give starting material, mono-transesterified, two ditransesterified, tritransesterified and fully transesterified products. The mono and ditransesterified products were metallated and reacted with the acid chloride of 5-carboxyphenyl-10,15,20-tritolylporphyrin (**16**) (prepared by a mixed-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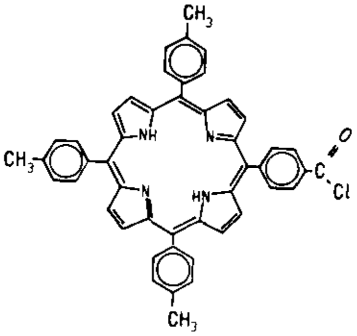
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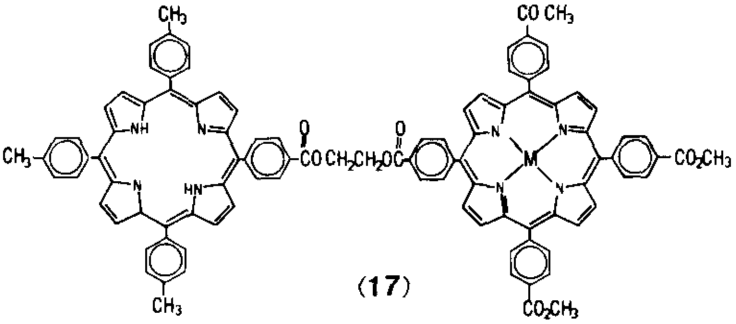
aldehyde synthesis) to give the bisporphyrin (**17**) and trisporphyrins one of which is shown (**18**).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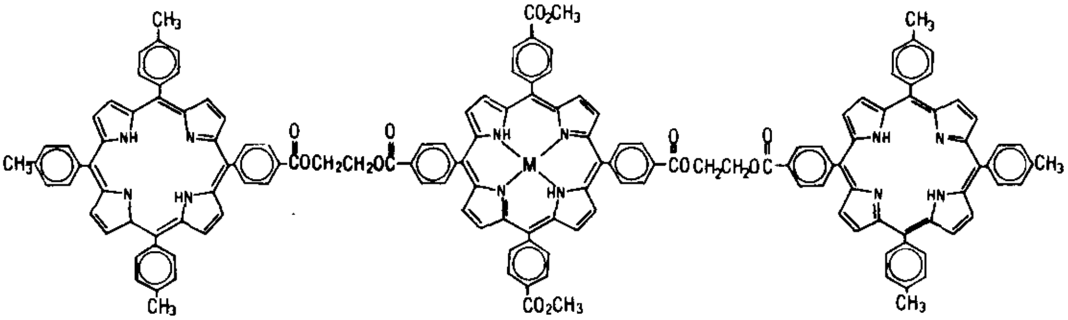
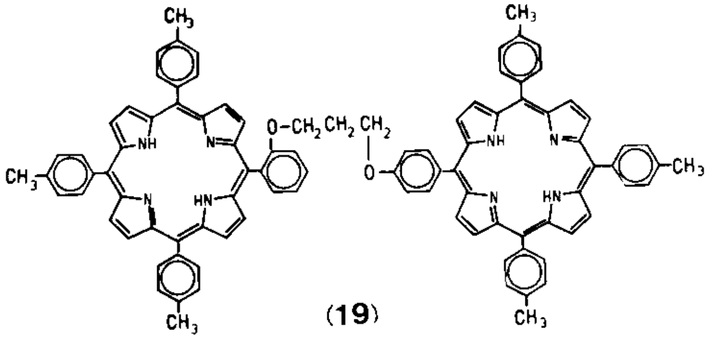

(18)

Little,[11] extending his work on oxygen binding models, employed a simple *high yield ether linkage for the synthesis of the bisporphyrin* (**19**). 5-(2-Hydroxyphenyl)-10,15,20-tritolylporphyrin was reacted with a greater than 10 fold excess of 1,3-dibromopropane in refluxing dimethylformamide in the pres*ence of potassium* carbonate for 24 hours to yield the 3-bromoalkylporphyrin (**20**). This was reacted with two fold excess of 5-(4-hydroxyphenyl)-10,15,20-

tritolylporphyrin to give, after gel permeation chromatography, the bisporphyrin.



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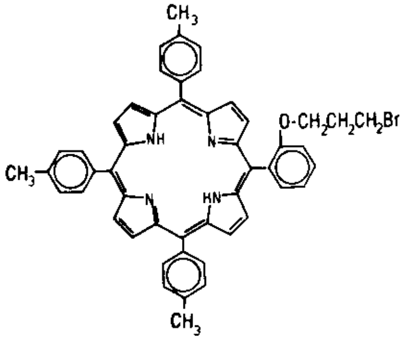
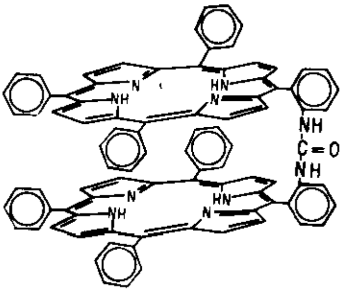


(20)

Landrum et al.[12] adapted the previously reported work of Collman et al.[13] to give a singly linked bisporphyrin (**21**). This was then treated with $FeBr_2$ or $MnBr_2$ to give the metallobisporphyrin and subsequently treated with tetrabutylammonium imidazolate in dry tetrahydrofuran to give the imidazolate bridged bisporphyrin (**22**).



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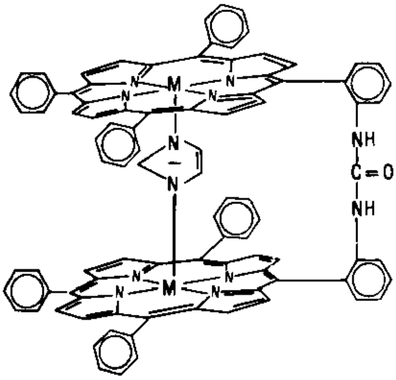

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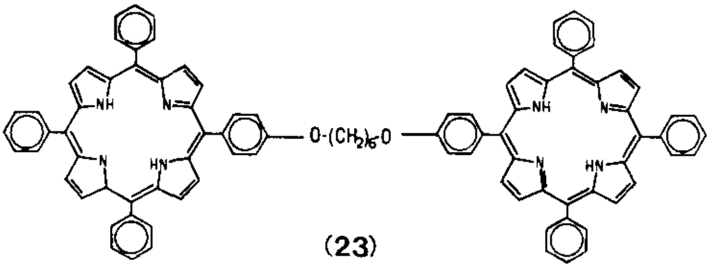
Zingoni[14] treated 5-(p-hydroxyphenyl)-10,15,20-triphenylporphyrin with 1,6-ditosyloxyhexane and anhydrous potassium carbonate in DMF for 24 hours at room temperature. Purification by chromatography on an alumina column with dichloromethane as eluant produced the TPP dimer (**23**) in 77% yield. This was then reduced with p-toluenesulfonylhydrazine in pyridine in the presence of anhydrous potassium carbonate at 105° to yield the bacteriochlorin dimer (**24**).



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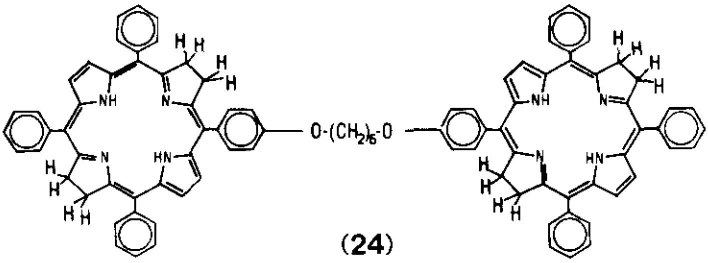

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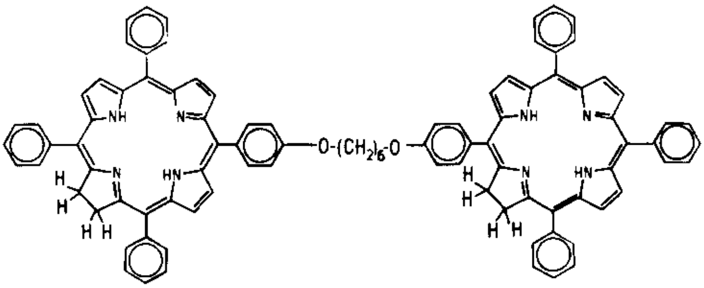
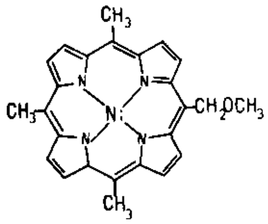
Partial oxidation of the bacteriochlorin dimer with equimolar DDQ in benzene produced the chlorin dimer (**25**) as a mixture.



(25)

In a singular departure from the more usual work in the field, Maltzan[15] reacted meso-tetramethylporphyrin with N-Bromosuccinimide to obtain the bromomethyl and the β-bromo substituted products which were then reacted to form polymers. The bromomethyl compound was converted to the methoxymethyl (**26**) with sodium methoxide/methanol. Subsequent reaction with meso-tetramethylporphyrin in chloroform and bubbling HCl gas gave the bisporphyrin (27) in 70% yield. The Ni-Ni and Ni-Pd dimers were produced by appropriate metallation



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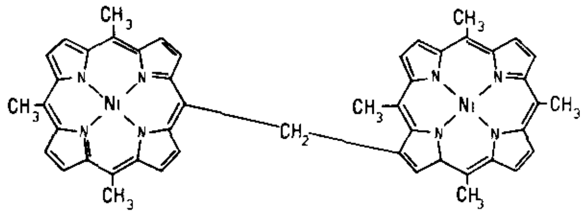


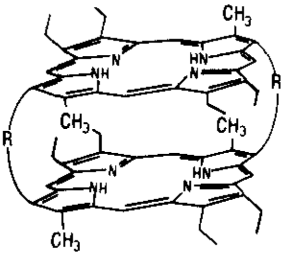
(27)

of the monomers with subsequent coupling. This was the first reported example of a meso-beta' dimer (also linked solely through carbon) but is clearly not capable of much generalization.

While a single covalent link ensures that two porphyrins are held in close proximity the conformations of such species in solution may be numerous. While determining such conformations can in itself be interesting and rewarding, there are situations in which one would like to have better control over the relative disposition of the two macrocycles. In an attempt to meet this criteria the synthesis of doubly linked porphyrins was undertaken.

It should be pointed out that strati-bis-porphyrins linked only twice (at diametrically opposite beta-positions) can exist with the porphyrin rings either parallel or anti-parallel. If the linkages are sufficiently short, the porphyrin units cannot rotate past one another, and the dimer would therefore exist as a mixture of the meso (parallel) and dl (antiparallel) substances. Such a mixture tends to be difficult, if not impossible, to separate, especially in the absence of extraneous functional groups. To date, no one has reported a resolution of such a mixture.

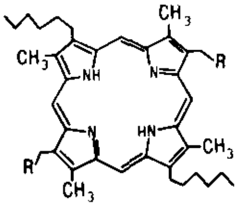
In 1977 Ogoshi et al.[16] reacted 7,17-bis-(2-carboxyethyl)-2,3,12,13-tetraethyl-8,18-dimethylporphyrin with isobutyl chloroformate in tetrahydrofuran; this was highly diluted and added dropwise to a tetrahydrofuran solution of 7,17-bis(3-hydroxypropyl)-2,3,12,13-tetraethyl-8,18-dimethylporphyrin to give the doubly linked bisporphyrin (28).



$R = -CH_2CH_2CO_2CH_2CH_2CH_2-$

(28)

Chang et al.[17] synthesised the porphyrin (**29**) R=COOH or R=CH_2COOH, and manipulated the side chains to give R=$CH_2NR'H$ or R=$CH_2CH_2NR'H$. High dilution coupling of pairs of these porphyrins gave a series of cofacial dimers (**30**).



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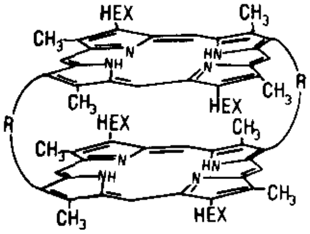


$R = CH_2CH_2CON(n\text{-}Bu)CH_2CH_2CH_2$

or

$R = CH_2CON(n\text{-}Bu)CH_2CH_2CH_2-$

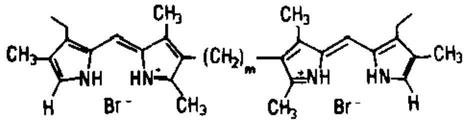
or

$R = CH_2CON(n\text{-}Bu)CH_2CH_2-$

(30)

Various metal ions were incorporated at the monomer stage to give mixed metal systems. In order to relieve the low solubility discussed above, hexyl side chains were used to enhance the solubility in organic solvents.

In our laboratory, to avoid the usual difficulties with long-term stability, we sought to prepare strati-bis-porphyrins linked solely through carbon-carbon bonds, as our singly-linked dimers had been.[6] The obvious route entailed a head-to-tail coupling of the dimeric pyrromethenes (**31**) used in our earlier work. To minimize polymerization, the reaction had to be effected under conditions of high dilution, and hence only Johnson's[18] stepwise porphyrin synthesis would serve. Tetrabromination of the dimeric pyrromethenes (**31**), for which a new procedure had to be devised to ensure maximal yield and



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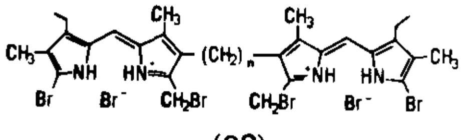
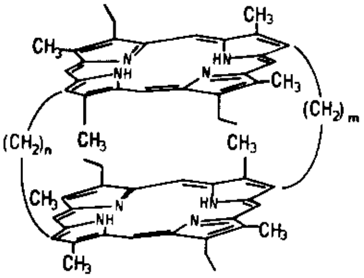


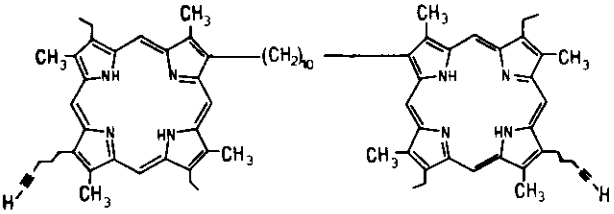
(32)

purity,[6] afforded dimeric pyrromethene (32), which was reacted with its alpha-free precursor (or analog) under high dilution (stannic chloride- dichloromethane) to give a doubly linked bis-biladiene, whose cyclization under the usual conditions gave the bisporphyrin (33) in moderate yield. As the synthesis was stepwise, the two linkages needed not be of the same length, enabling a synthesis of unsymmetrical, "tilted" strati-bis-porphyrins, as well as symmetrical ones.



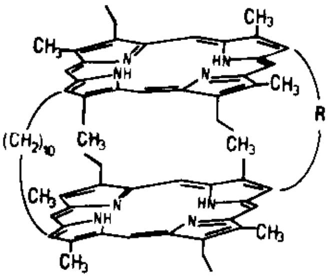
(33)

Alternatively, we hoped to form the two linkages in stepwise fashion via means of an acetylenic coupling to achieve the second linkage.[19] A singly-linked bisporphyrin was constructed (as for our earlier dimers) bearing hydroxypropyl groups opposite the linkage in both porphyrin units. These were converted via the bromopropyl function to the pentyne side chain derivative (34) which was then cyclized by oxidative coupling of the terminal acetylenes



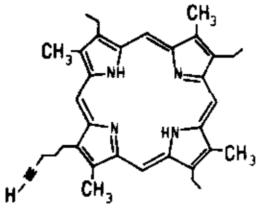
(34)

at high dilution to yield the cyclic bis-acetylene (35). Models (such as (36) and its oxidatively derived dimer) suggest that it will be possible to hydrogenate the diacetylenes to alkane without affecting the porphyrins provided the latter are suitably metallated.



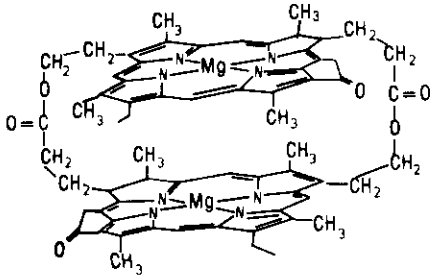
(35)

$R = -(CH_2)_3-C\equiv C-C\equiv C-(CH_2)_3-$



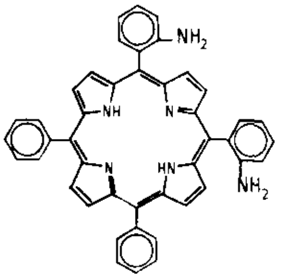
(36)

Chlorophyll derivatives have also been doubly linked to form the "sandwich" dimers. Wasielewski et al.[20] converted pheophytin *a* to methylpyropheophorbide *a* and effected an indirect anti-Markownikoff hydration of the vinyl group by means of the thallium trinitrate oxidation to the aldehyde acetal, followed by hydrolysis and cyanoborohydride reduction. The methyl ester was hydrolysed in HCl to yield the hydroxy-acid which was self-coupled with 2-chloro-N-methylpyridinium iodide in the presence of triethylamine and 4-dimethylaminopyridine in refluxing butyronitrile. Magnesium was inserted with iodomagnesium-2,6-di-tert-butyl-4-methylphenolate in refluxing dichloromethane to give the chlorophyll dimer (**37**).



(37)

A number of tetraarylporphyrins have been subjected to multiple linkage. Collman et al.[13] condensed pyrrole (2 eq) with benzaldehyde (1 eq) and 2-nitrobenzaldehyde (1 eq) in acetic acid to give a mixture of tetraphenylporphyrin and mono, di, tri and tetranitrophenylporphyrins. Chromatographic separation gave the diphenyldinitrophenylporphyrins. These were reduced with $SnCl_2$/HCl to give the α,α-trans and α,α-cis diaminophenyl-diphenylporphyrins (**38**). The α, α-trans diaminophenyl-diphenylporphyrin was treated with excess phosgene followed by a second equivalent of itself to give the bisporphyrin (**39**). The same procedure using the α, α-cis diaminophenyl-diphenylporphyrin resulted in the two bisporphyrins (40) and (41). Reaction of α, α-cis diaminophenyl-diphenylporphyrin with mesoporphyrin IX diacid chloride resulted in bisporphyrin (42).



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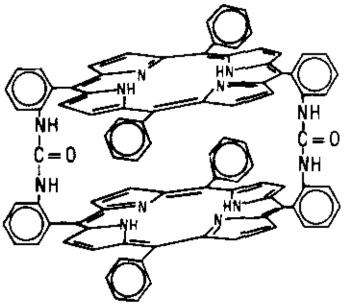

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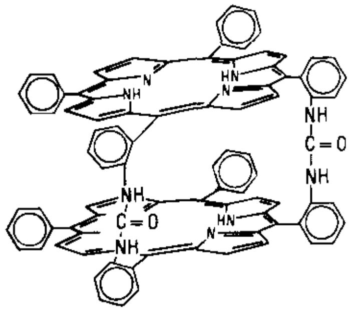

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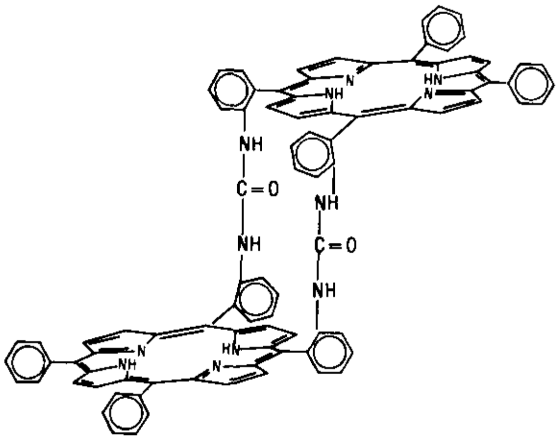

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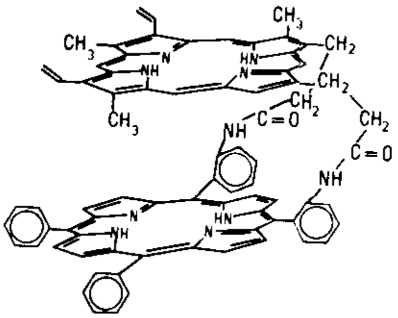
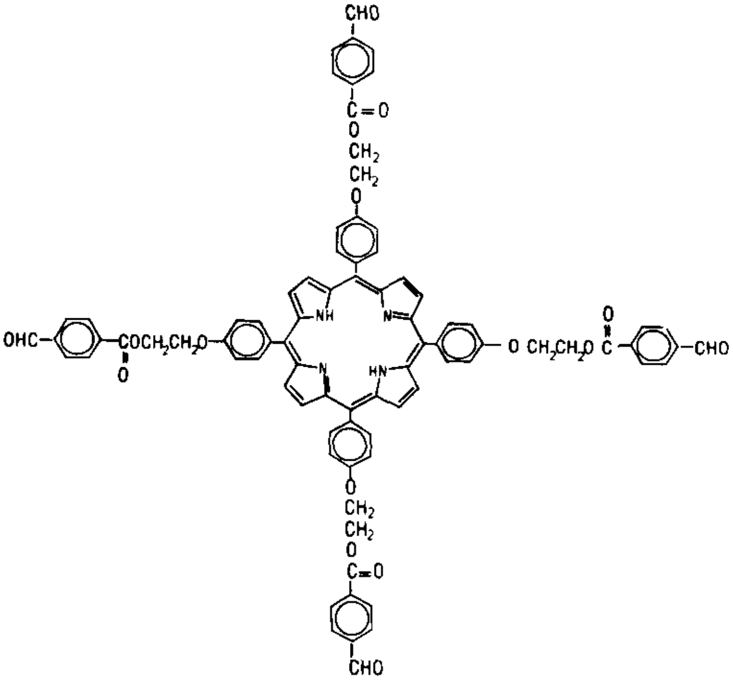


(42)

Porphyrin dimers linked four times have been prepared as well. If applied to β-octaalkyl porphyrin dimers, four links would remove the ambiguity of orientation inherent with dimers linked only twice (through diametrically opposite beta-positions), and result in a single, well defined substance. Such a synthesis has yet to be reported.

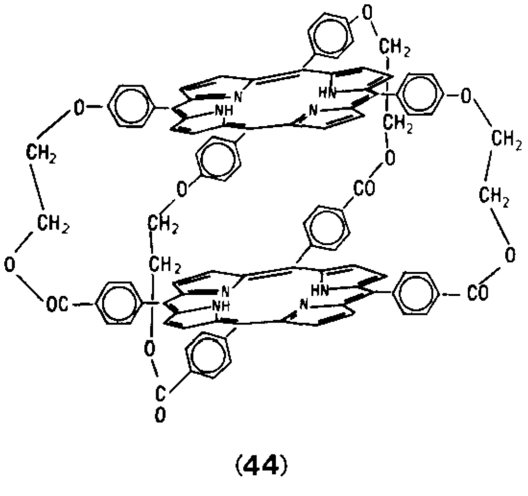
In the context of meso-tetraaryl porphyrin chemistry, even two linkages (through opposite meso-positions) will result in but a single isomer. The two additional linkages were added more to discourage slippage or tilting of the two porphyrin units with respect to each other, and to provide a more rigidly defined geometry thereby. The only example reported so far is by Kagan.[21]

The enormous problems of producing four covalent links between two porphyrins was overcome by the synthesis of the second porphyrin in situ at the ends of the four links in a similar manner to that used by Almog et al.[22] in the synthesis of capped porphyrins. Kagan et al. took p-2-hydroxyethoxybenzaldehyde and reacted it with pyrrole in refluxing acidified xylene followed by esterification with the acid chloride of p-carboxybenzaldehyde to give (**43**).



(43)

Reaction of (**43**) with pyrrole (4 eq) in refluxing propionic acid/ethylbenzene gave the tetra linked bisporphyrin (**44**).



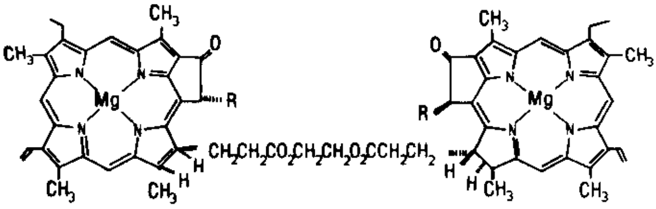
(44)

Spectral Properties

The presence of two close and interacting chlorophyll molecules in P-700 has been suggested by NMR and ESR.[23] Chlorophyll a adducts with ethanol or water have been prepared which mimic the optical and ESR properties of P-700.[24] Several structures for P-700 have been put forward,[25] the major structural facet being the hydrogen bonding of a polar molecule between the magnesium of one chlorophyll and the ring V keto carbonyl of the second chlorophyll. The adduct formation showed a highly unfavorable entropy factor indicated by high chlorophyll concentration at low temperatures (77K). This can be removed by the expedient of covalently bonding the two chlorophylls together to prevent diffusion of the reactive sites.

Any P-700 models thus formed should mimic certain characteristics of P-700. They should have a red shifted absorption compared to the monomer from 677nm to 700nm (780nm to 870nm for bacteriochlorophyll), should exhibit similar ESR and NMR spectra and should undergo photobleaching reactions.

The magnesium free diester (**45**) of Boxer and Closs[7] had visible absorption and fluorescence spectra indistinguishable from the monomer, showing no chromophore interaction. The bispyrochlorophyllide a (**46**) also showed no differences in dry benzene but in wet benzene a red shift was observed in the absorption spectra of 666nm to 696nm, and to 717nm in emission.



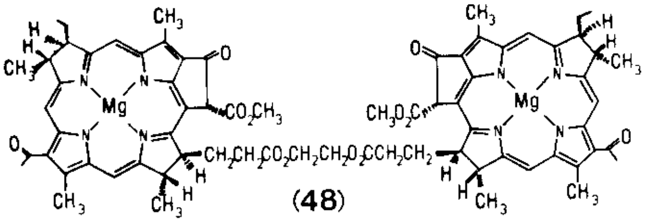
(45) M = H_2 R = -H
(46) M = Mg R = -H
(47) M = Mg R = $-CO_2CH_3$

The ^1H NMR resonances were broad in dry benzene but sharpened on the addition of water. The addition of pyridine-d_5 caused further chemical shift differences attributable to a strong coordination to the magnesium ion thus preventing close association of the chromophores. ^1H NMR also showed the maximum overlap in rings III and V.

The bischlorophyll a (**47**) of Wasielewski[8] again showed a dependence on the addition of polar molecules to produce the red shift from 677nm to 697nm; water, ethanol, methanol and primary alkanethiols were all used. The ability of non-aqueous hydrogen bonding ligands to induce the red shift opens up the possibility that amino acid residues in the protein may be responsible for the P-700 formation. Several nonpolar solvents were also used suggesting a hydrophobic environment around the special pair as in the hemoglobin system. The ^{1}H NMR closely resembled the monomer with broadened peaks, this being due to the equilibrium of stereoisomers at C-10 established in polar solvents giving a 3:1 mixture of a-a and a-a' diastereomers. The system was shown to undergo photobleaching with I_2, the 697nm absorption being bleached in 10 minutes in the dark and 30 seconds in red light. The ESR signal from the bleached system corresponded to that expected from an electron delocalised over both chlorophyll *a* molecules and compared with that observed with P-700 in *Chlorella vulgaris*.

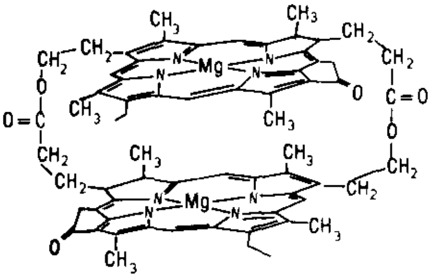
It was observed that some absorption remained at 677nm even with polar solvent and after photobleaching. This was attributed to the 25% a-a' dimer which would not fold to give the hydrogen bonded dimer due to steric interactions of one carbomethoxy group between the macrocycles.

The bisbacteriochlorophyll *a*[9] (48) was analogous to the bischlorophyll *a*, the absorption being red shifted from 780nm to 803nm but not sufficiently to account for the 865nm of bacteriochlorophyll *a* special pair. The ^{1}H NMR was consistent with the dimer structure as in the chlorophyll *a* model. Thus the C-2 acetyl takes no part in the hydrogen bonding of the model system but could possibly *in vivo*. The system did undergo photobleaching and exhibited an absorption at 1150nm as opposed to the 1250nm absorption of the special pair cation radical.



(48)

The bis(chlorophyll)cyclophane[20] (49) showed no solvent dependence in its absorption and ^{1}H NMR spectra, these being unchanged from the monomer. No 700nm absorption could be produced and the photo oxidation product showed a line width in the esr indicative of the electron delocalized over the two macrocycles. The ^{1}H NMR indicated that the stacking is central as opposed to the maximum overlap of rings III and V in the singly linked bischlorophyll a.

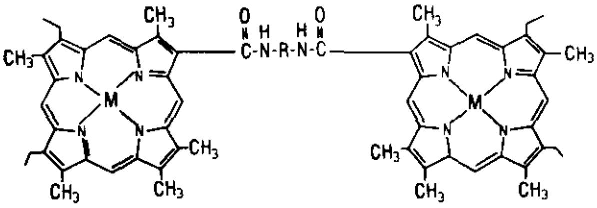


(49)

The chlorophyll special pair models could be judged to be successful if they mimic the properties of the in vivo system. The bisporphyrins on the other hand have no obvious criteria to meet.

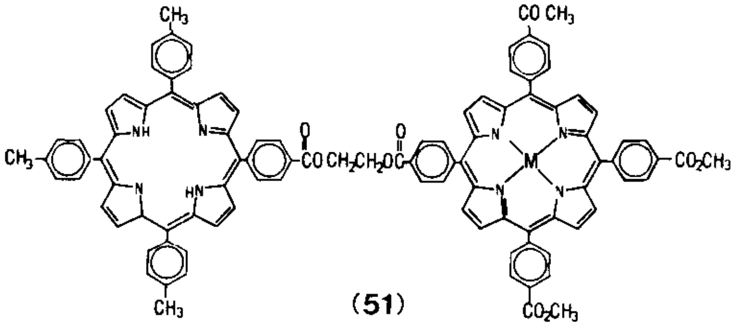
The bisporphyrins are thus synthesised and their properties observed, the interactions between macrocycles and metal-metal interactions being a possible measure of their usefulness. To determine these interactions the absorption, emission, fluorescence and phosphorescence spectra are often compared to the monomer.

Schwarz et al.[1] found no difference in the absorption spectra of their singly linked bisporphyrin (**50**) but emission spectra at 77K showed triplet-triplet interaction for the ethylene bridged system, manifested as a shortening of the zinc porphyrin triplet state lifetime and quenching of the zinc porphyrin phosphorescence.



(50)

Anton et al.[26] found no difference in the absorption spectra of their dimer (**51**) or trimers (**52**) with respect to their monomers (**53**) and (**54**). The ^1H NMR spectra were also the sum of the monomer spectra plus resonances for the 8 protons of the ethylene links which appeared at 4.93ppm.



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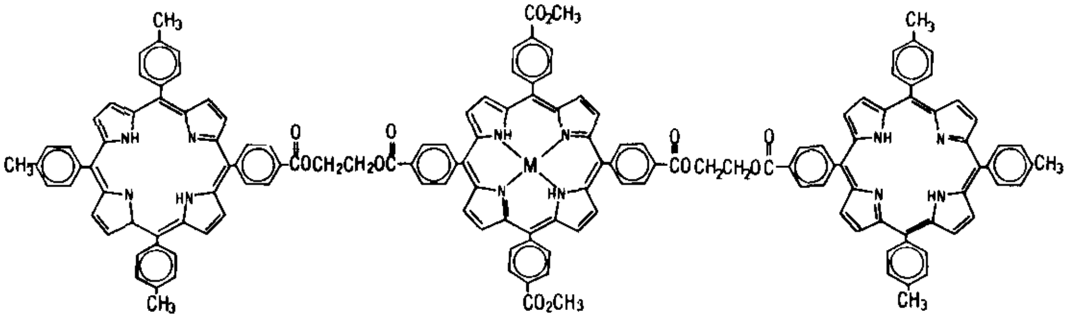

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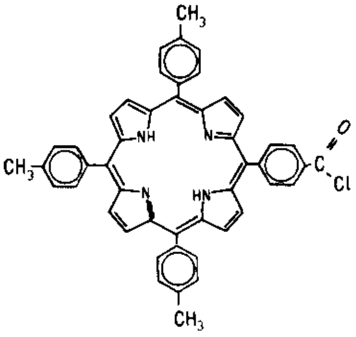

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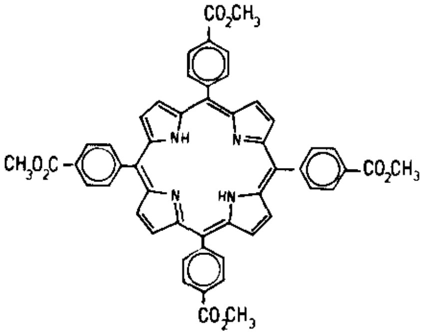
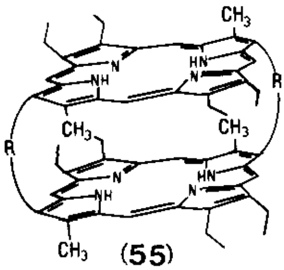


(54)

Ogoshi[16] also noticed no shifts in the absorption spectra of the di-zinc complex of their bisporphyrin (55) but did observe incomplete incorporation of

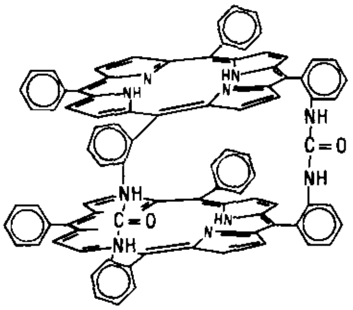


(55)

R = $-CH_2CH_2CO_2CH_2CH_2CH_2-$

zinc on treatment of zinc acetate/methanol. The proton NMR spectra exhibited 9 signals for the 8 meso protons between 9-10ppm attributed by the author to an equal mixture of the syn and anti stereoisomers. In the zinc complex the meso protons are centered about 10ppm in a narrower band of 0.2ppm which the author saw as indicative of a more face to face configuration than with the free base which had a parallel displacement resulting in higher magnetic field shifts due to the ring currents of the porphyrins. A similar trend was observed with the methyl resonances as would be expected.

Collman et al.[13] found no spectral changes for their porphyrins which were not cofacial (**56**) and (**57**) but in contrast to Ogoshi found that Soret bands of (**58**) and (**59**) had been blue shifted by approximately 15nm in the free base porphyrins and 4-5nm for the cobalt and copper complexes. ESR spectra of the cobalt and copper complexes of (**58**) and (**59**) show hyperfine splitting consistent with metal-metal separation of approximately 6.5Å.



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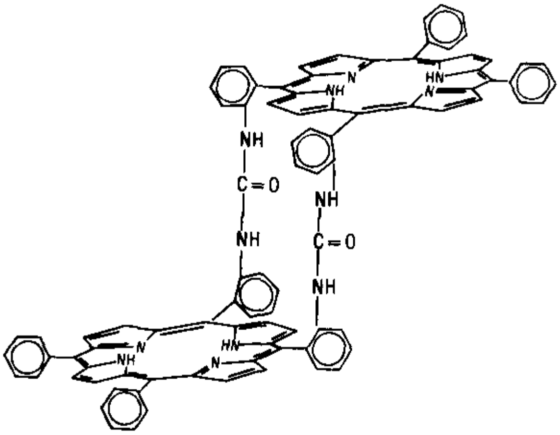

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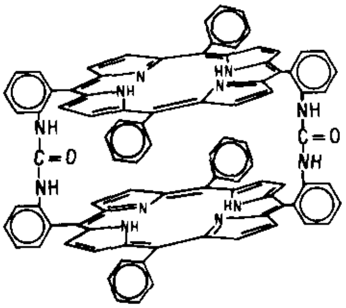

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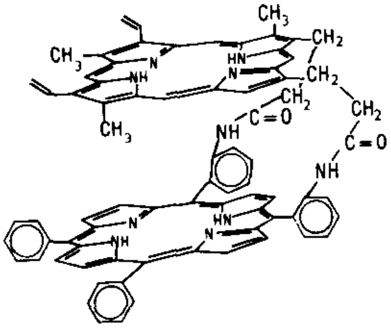
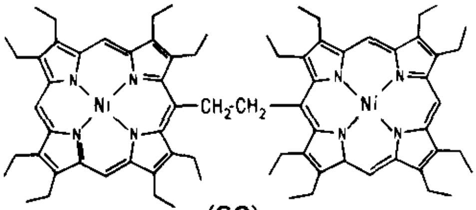


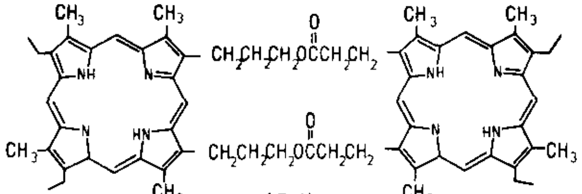
(59)

Unlike the previous singly linked bisporphyrins whose synthesis had been deliberate, Arnold et al.[2] had produced a nickel porphyrin whose broadened Soret band, red shifted by 11nm and visible bands 3nm red shifted, had led them to identify the product as a bisporphyrin (**60**), and whose identification was confirmed by mass spectrometry.



(60)

Ichimura[3] observed a blue shift of 8nm in the Soret of (**61**) and greater than 10nm for the zinc and copper dimers with small red shifts in the visible bands. The trimer (**62**) showed a split Soret, one band blue shifted with small red shifts of the visible bands. The zinc complexes showed considerable self quenching of fluorescence, whereas the magnesium complexes exhibited only slight decrease in fluorescence intensity.



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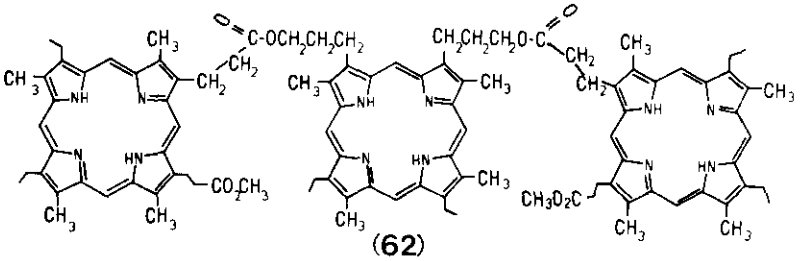
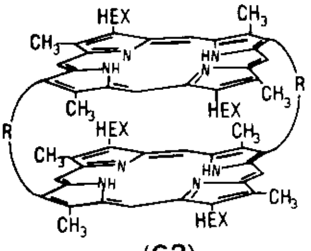


(62)

Chang[27] found blue shifts of 14-16nm in the Soret with red tails for his bisporphyrins (**63**) with small red shifts in the visible region. In the copper, zinc and magnesium complexes the Sorets were blue shifted. These results were explained in terms of exciton coupling between two parallel transition dipoles. The shifts would depend on two components, a solvent parameter representing the difference in the effect of solvation of the ground and excited states, and the nature of the exciton coupling which would depend on the geometry of the dimer.



(63)

$R = -CH_2CH_2CON(n\text{-}Bu)CH_2CH_2CH_2-$

or

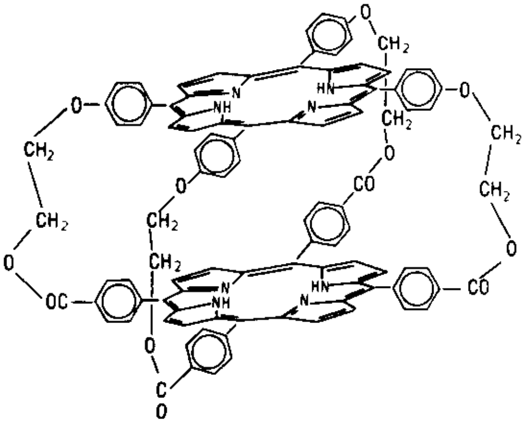
$R = -CH_2CON(n\text{-}Bu)CH_2CH_2CH_2-$

or

$R = -CH_2CON(n\text{-}Bu)CH_2CH_2-$

If the dimer geometry was of ideal D_{4h} symmetry, the result would be a blue shift to the Soret band, tempered by a red shift due to the solvent parameter. However, tilting or sliding of the porphyrin planes would cause fluctuation of higher exciton levels and develop the lower exciton levels which was a possible explanation to the red tail in the 450nm region. In the visible region the solvent parameter and inhomogeneous solvent broadening were considered comparable in magnitude to the exciton coupling parameter resulting in the small red shifts. The model predicted fluorescence quenching but not to the magnitude shown by the dimers and this was believed to be a manifestation of the red tail in the Soret enhancing self-quenching.

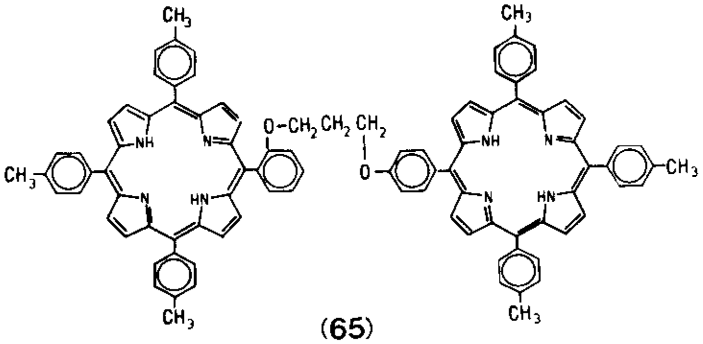
Kagan et al.[21] found absorption and emission spectra of their tetra linked bisporphyrin (**64**) to be broadened and red shifted in the free base. The zinc complex had a broadened but unshifted Soret band while the visible band and emission spectra were both red shifted and broadened. Quenching was also



(64)

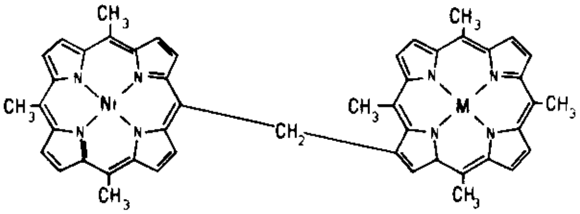
observed in the emission spectrum. The proton NMR showed A_2B_2 degeneracy of the phenoxy and benzoyl ring protons of the monomer split into AA'BB' quadruplets as the interior and exterior facing protons are not distinguishable. The alkyl protons appeared as AA'BB' multiplet due to the restricted rotation of the O-C-C-O bonds.

Little[11] found no positional shift in the absorption spectra of (**65**) but found the intensity of the Soret was only 70% of that expected, apparently the result of a splitting of the Soret observed as a distinct shoulder to the red. Identical spectra were obtained in different solvents ruling out the possibility of two species, folded and unfolded, being present. The ESR spectrum was the sum of the simple monomers and no metal-metal interaction could be observed.



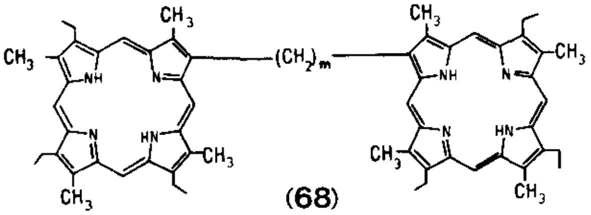
(65)

Maltzan[15] observed a split Soret red shifted 7-15nm for his Ni-Ni (**66**) and Ni-Pd (**67**) dimers. The visible band in the Ni-Ni dimer was also slightly red shifted which he attributed to meso substitution effects. Variable temperature ^{1}H NMR was used to assign the configuration and confirm that rotation about the methylene linkage was restricted.



(66) M = Ni
(67) M = Pd

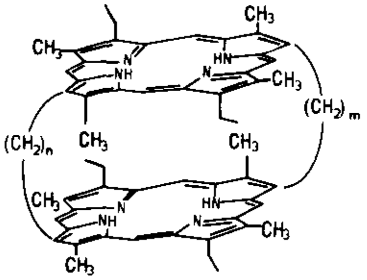
Dolphin et al.[28] in the series of porphyrins (**68**) m = 0-8 found no difference in the spectra of m = 8 and the monomer, aetioporphyrin I, but when m = 1 and 0 the Soret was broadened and red shifted in the free base. The protonated porphyrin gave a red shifted split Soret the visible bands also being red shifted. The well resolved dication doublet was explained by considering that the Soret of the dication monomers arise from doubly degenerate excited states. They can be considered to interact in pairs resulting in four dimer excited states. For m = 0 the transition dipoles would be expected to be parallel to the vector between centers resulting in a red shifted low energy state and perpendicular to the vector between centers resulting in an unshifted or blue shifted state. The ^{13}C NMR for $m \geq 3$ showed the porphyrin nuclei to be pseudosymmetrical, the meso carbons giving a single broad band. For m = 0 or 1, the meso carbons were resolved into four well defined peaks. For m = 2 the meso carbons appeared as a 6:2 doublet.



(68)

The doubly linked dimers of Paine[6] showed shifts in the absorption spectra apparently dependent upon the length of the links and the orientation of the two porphyrin links. The shorter the links the larger the shift assuming both links are shortened equally. Shortening one link appears to reduce the interaction, presumably by tilting the macrocycles and the C_{8-6} has less shift than the C_{8-8}.

The dimer (**69**) m = n = 8 had a blue-shifted Soret of 8nm in the Zn-Zn complex, 3nm for the protonated species and 9nm for the free base compared to OEP. The dimer (**69**) m = n = 10 was similar to C_{8-8} with slightly smaller

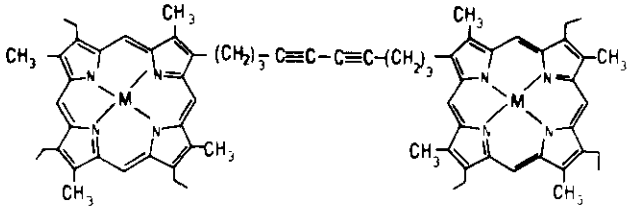


(69)

shifts being observed. Dimer (**69**) m = 8, n = 6 had smaller shifts than the C_{8-8}, the Zn-Zn complex had 3nm shifted Soret, the protonated species 2nm and the free base 7nm.

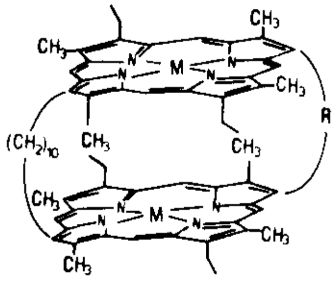
The C_{5-5} dimer (**69**) (m = n = 5) had the largest Soret shifts, the Zn-Zn complex 14nm, the protonated species 14nm and the free base 13nm. The visible bands had smaller shifts and varied from 2nm blue shift for the C_{8-8} Zn-Zn dimer to 4-5nm red shifts in the C_{8-8} free base. The protonated species' visible bands were not changed.

The singly linked diacetylene Zn-Zn complex[19] (**70**) showed a 5nm blue shift in the Soret and smaller blue shifts of the visible bands compared to the monomer. The free base (**71**) and protonated species (**72**) showed no changes in their visible spectra.



(70) M = Zn
(71) M = H_2
(72) M = H_4^{2+}

The doubly linked diacetylene Zn-Zn dimer (**73**) showed a much larger 14nm blue shift in its Soret with small red shifts in the visible bands compared to its singly-linked Zn-Zn precursor. The free base (**74**) in this case, however, did show a 7nm blue shift in the Soret and small red shift in the visible bands. The protonated dimer (**75**) also showed a blue shift in the Soret but of only 4nm whereas the visible bands had minimal red shifts.



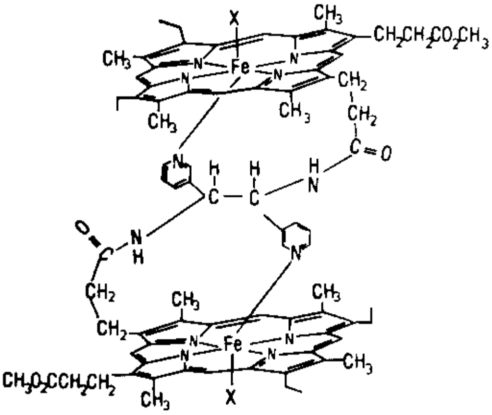
(73) M = Zn
(74) M = H_2
(75) M = H_4^{2+}

R = $-(CH_2)_3C{\equiv}C-C{\equiv}C(CH_2)_3-$

Applications

The chlorophyll model systems have developed our understanding of the photosynthetic process. The determination of the mechanism by which photoenergy is converted to chemical energy is a major goal in the efficient harnessing of this energy resource. The chlorophyll dimers of Boxer and Closs[7] and Wasielewski et al.[8] proved to be good models for the P-700 photocenter. The bacteriochlorophyll dimer[9] did not however mimic the P-870 and other factors must be considered in this case.

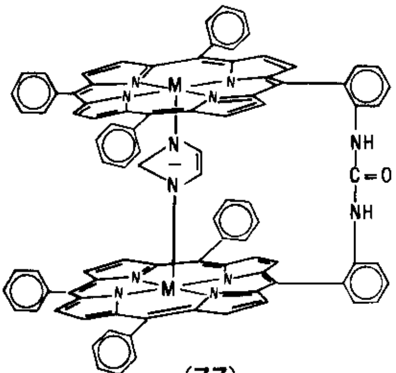
Traylor's[4] bisporphyrin (**76**) is a model system for heme oxygen binding.



(76)

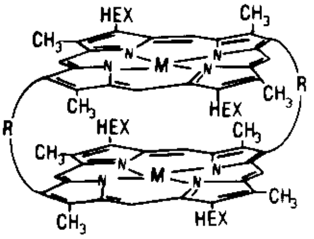
The dimer was found to bind oxygen reversibly, a characteristic shown by other monoheme models[29], but unlike other models it reacted with carbon monoxide with two different rate constants, displaying a cooperativity effect, an effect shown by hemoglobin. The double rate constant was explained by considering that the strain imposed by the short link caused base elimination of one of the heme groups giving a partially 4-coordinate form. This fast reacting form binds CO rapidly and closes to a 6-coordinate state, the second heme then proceeds to bind CO slowly without base elimination. Half oxidation of (**76**) resulted in the disappearance of the fast rate which would be expected as the faster reacting form would oxidise first.

Landrum's[12] imidazolate bridged bisporphyrin (**77**), an attempted cytochrome oxidase model, showed significant anti-ferromagnetic coupling, thus there is heme-heme interaction, but the J values did not compare to those of cytochrome oxidase. The authors considered the metal-metal distances too large and other ligands might possibly bring them into closer proximity.



(77)

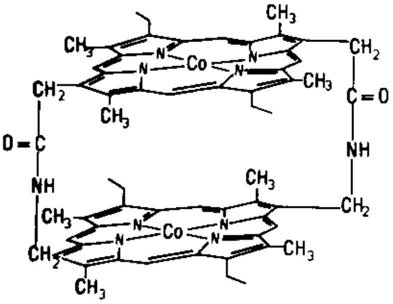
Chang[30] carried out partial electrolytic reduction of (**80c**) Mg-Mg and obtained a violet solution (λ_{max} 670nm) which was believed to be the monocation radical. EPR measurements showed a single line, g = 2.003, with a peak separation of 1.05 Gauss, less than half that of $MgOEP^+$ radicals under the same conditions. The narrowing of line width indicates extensive electron exchange between the macrocycles similar to that observed in P-700 and P-870.



(78) R = $-CH_2CH_2CON(n\text{-}Bu)CH_2CH_2-$
(79) R = $-CH_2CON(n\text{-}Bu)CH_2CH_2-$
(80) R = $-CH_2CON(n\text{-}Bu)CH_2-$
a M = Zn
b M = Co
c M = Cu

Chang[31] also investigated the possibility of multielectron reduction of oxygen by these dimers. Oxygenation of 5-coordinate imidazole complexes of (**78b, 79b, 80b**) showed two different behaviors. The larger metal-metal separation dimers (**78b, 79b**) formed reversible 1:1 $Co\text{-}O_2$ adducts with absorption spectra showing 395nm Soret with only a small shoulder at 417nm. The shorter metal-metal separation of (**80b**) showed a 2:1 $Co\text{-}O_2$ adduct which was not reversible on evacuation and showed an absorption spectrum with the major absorption at 417nm. Unfortunately Co(III)-X, oxygenated $Co\text{-}O_2$ and binuclear $Co\text{-}O_2\text{-}Co$ all have near identical absorption bands so only the rate and difference of reaction of (**80b**) can be observed. The oxygen adduct of (**80b**) was believed to be the μ-peroxo dicobalt complex ($Co\text{-}O_2\text{-}Co$) which is diamagnetic and shows no EPR signal. However, treatment with I_2 should yield a 15 line EPR spectrum if it becomes oxidised to the μ-superoxo dicobalt complex, this indeed was observed. The iron bisporphyrins showed similar behavior, however, addition of oxygen to (**80a**) resulted in spontaneous oxidation of the heme even at -45°C. The rate of reaction was rapid due to the favorable position of the two hemes for the formation of the μ-peroxo complex, the rate determining step in monohemes.

Collman et al.[32] carried out a series of experiments with a range of porphyrin dimers. As in Chang's earlier work a short M-M distance dimer (**81**) showed considerable catalytic activity to the reduction of oxygen without the production of significant hydrogen peroxide. The bisporphyrin was introduced onto a pyrolytic graphite disk by adsorption from dilute dichloromethane solution. Rotating disk experiments were carried out with the graphite disk and a platinum ring in 0.5M perchloric acid or 0.5M trifluoroacetic acid with oxygen at atmospheric pressure. For longer linked bisporphyrins and Co-Pd (**81**) considerable hydrogen peroxide was formed. However no hydrogen peroxide was formed with (**81**), a hydrogen peroxide containing solution without oxygen was tested to show that it did not reduce or disproportionate hydrogen peroxide. The ability of (**81**) to reduce oxygen was found to be dependent on the availability of protons; unbuffered solutions tend to produce hydrogen peroxide when the supply of protons is exhausted.



(81)

With the great interest being shown in activated surface catalysts the possibilities for the bisporphyrins seem numerous. The coordination and reduction of small molecules such as oxygen and nitrogen, polymerisation of small organic molecules such as ethylene, the splitting of water and many other areas in which polynuclear catalysts are being investigated could well find solutions in bisporphyrins.

Acknowledgments

This work was supported by the United States National Institutes of Health (AM 17989) and the Canadian National Science and Engineering Research Council grants.

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Received, 13th October, 1980