Electroorganic reactions. Part 55.† Quinodimethane chemistry. Part 3. Transition metal complexes as inter- and intra-molecular redox catalysts for the electrosynthesis of poly(*p*-xylylene) (PPX) polymers and oligomers‡

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The role of metal complexes as redox mediators in the electrosynthesis of poly(*p*-xylylenes) (PPXs) has been explored, with a view to designing metal-containing precursors that can act both as mediators and starting materials for metal-containing polymers. A number of transition metal complexes [Cr(III), Ni(II) and Co(II)] are efficient redox catalysts for production of quinodimethanes, and hence PPXs. Following encouraging results from experiments using mediators based on anthranilic acid and salicylaldehyde ligands a macrocyclic compound was designed, and successfully prepared by a convergent route that incorporated both a 1,4-bis(chloromethylarene) function as a precursor to a quinodimethane and a Ni(II) salen unit as an intramolecular redox catalyst. The macrocycle was successfully reduced cathodically to yield a PPX polymer with bound Ni(II). Evidence is presented for the operation of intramolecular redox catalysis (homomediation).

Introduction

The electrochemical reduction of 1,4-bis(bromomethyl)-benzene gives[1,2] poly(*p*-xylylene) (PPX), presumed to arise *via* 2 F 1,6-elimination of two bromide anions with formation of *p*-xylylene, the parent quinodimethane (QDM). Because the conditions (room temperature, atmospheric pressure) are less drastic than for pyrolytic generation the electrochemical route has been extensively investigated for the formation[3,4] of PPXs and poly(*p*-phenylvinylenes) (PPVs). Furthermore, *o*-quinodimethanes, important intermediates for cycloaddition reactions, may be generated in the presence of dienophiles, and thus effect useful synthetic conversions.[5,6] A limitation of this electrochemical reduction route was that with few exceptions bis(bromomethyl)arenes must be used, as the cheaper and less lachrymatory chloro derivatives are more difficult to reduce and in many cases give cathodic hydrogenolysis.

We have shown[7] that quinodimethanes may be generated electrochemically and characterised by cyclic voltammetry and, in some cases, by NMR spectroscopy. The major follow-up reactions are polymerisation to give PPXs, oligomerisation or, for co-electrolysis, co-polymerisation. We also found[7] that generation of the QDMs, with subsequent oligomerisation or polymerisation, could be effected by redox catalysis using organic mediators.

Transition metal complexes have also been used as redox mediators in organic electrosynthesis. In particular, nickel complexes have been used for the electroreductive coupling of aryl halides[8,9] and the electropolymerisation[10] of 1,4-dihalobenzenes to poly(*p*-phenylene). Coupling between benzal dichloride ($PhCHCl_2$) and stilbene has been catalysed[11,12] by the reduction of Ni^{II}(salen) [salen = bis(salicylidene)ethylenediamine]. Furthermore, carbon–carbon bond formation results from electroreductions of a variety of alkyl and aryl halides in the presence of palladium[13,14] and cobalt[11] complexes. An important distinction must be made between those reactions that proceed by an inner sphere mechanism (*e.g.* oxidative addition to Ni^0) and those in which redox catalysis involves homogeneous outer sphere electron transfer (*e.g.* probably from Ni^I). Benzyl halides undergo[15,16] oxidative addition to Ni^0 complexes and bibenzyl results from reduction of benzyl chloride in the presence of $NiBr_2$bipy (bipy = 2,2′-bipyridine)[17] or $NiCl_2(PPh_3)_2$.[18] In the context of the present paper we have shown[16] that 1,4-bis(chloromethyl)benzene is electrochemically reduced to poly(*p*-xylylene) (PPX) in the presence of catalytic amounts of $Ni^{II}Cl_2L_2$ (L_2 = dppe or dppp) [dppe = 1,2-bis(diphenylphosphino)ethane, dppp = 1,2-bis(diphenylphosphino)propane]. In this case the balance of evidence was in support of an inner sphere mechanism involving oxidative addition of the dihalide to Ni^0L_2.

We present here the results of experiments in which we explore the formation of QDMs, with subsequent polymerisation or oligomerisation, in electrolyses of 1,4-bis(halomethyl)-arenes in the presence of relatively simple transition metal complexes. We have also constructed a QDM precursor in which the 1,4-bis(halomethyl)arene function and the complexed transition metal (Ni^{II}) are combined in the same molecule. The purpose is to demonstrate for practical purposes "intramolecular redox catalysis", in our case to produce a metal-containing polymer or oligomer. Intramolecular electron transfer between donor and acceptor groups has a long history[19] and recently a systematic study has explored[20] conditions and kinetics for intramolecular dissociative electron transfer in rigid 1,4-disubstituted cyclohexanes acting as donor–spacer–acceptor systems.

Results and discussion

Strategy and substrates: cyclic voltammetry of some transition metal complexes in the presence of 1,4-bis(halomethyl)arenes

The first step was to establish whether simple transition metal complexes were effective as external catalysts for the mediated

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‡ Dedicated to the late Professor Lennart Eberson.

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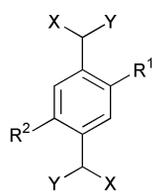
Table 1 Cyclic voltammetry of metal complex mediators and QDM precursors

Complex	Working electrode	$-E_p$(red)[a]/V *vs.* SCE	$-E_p$(ox)[a]3/V *vs.* SCE	$-E^0$/V *vs.* SCE	Precursor	$-E_p$/V *vs.* SCE
Co(salen)	Hg bead	1.30	1.21	1.25	**1a**	1.20[e]
Ni(salen)	Hg bead	1.67	1.60	1.63	**1b**	1.34[e]
$Cr(acac)_3$	Hg bead and Au	1.84[b]/2.2[c]	—	—	**1c**	1.52[e]
$CrCl_3 \cdot 6H_2O$	Hg bead	1.10[b]/1.6[c]	0.69	0.89[b]	**1d**	1.96
	Au	0.78[b]/1.65[c]	0.4	0.59[b]		
salen	Au	1.88			**1e**	2. 03
					1f	1.70

[a] $v = 200$ mV s^{-1}, DMF–Et_4NBr or Bu_4NBF_4. [b] First reduction peak. [c] Second reduction peak. [d] $v = 200$ mV s^{-1}, Hg bead, DMF–Et_4NBr. [e] First reduction peak.

electrolysis of 1,4-bis(halomethyl)arenes with consequent conversion into polymers or oligomers. The 1,4-bis(halomethyl)arenes involved in this initial phase are given as structures **1a**–**f**. The reduction potentials for these substrates, together with those of some common transition metal complexes, are displayed in Table 1.



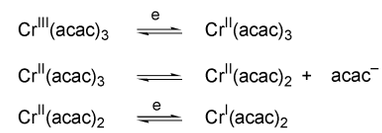
	X	Y	R^1	R^2
1a	H	Br	H	H
b	H	Br	OMe	H
c	Br	Br	H	H
d	H	Cl	H	H
e	H	Cl	OMe	OMe
f	Br	Cl	OMe	OMe

It is evident that the complexes are generally less easily reduced than the 1,4-bis(bromomethyl)arenes (**1a**–**f**) and consequently cannot be expected to act as redox catalysts. However, the corresponding dichlorides are reduced directly at potentials more negative than those for the transition metal complexes, and $CrCl_3$ is reduced slightly more easily than the dibromides **1a** and **1b**. Reductive cleavage to QDMs is in these cases possible in principle.

For the cyclic voltammetry of those complexes listed in Table 1, $CrCl_3$ gives[21] a quasi-reversible one-electron first reduction peak at $E_p(\text{red}) = -1.10$ V, corresponding to the Cr^{III}/Cr^{II} couple, followed by an irreversible two-electron peak corresponding to the Cr^{II}/Cr^0 system. The addition of compound **1d** ($E_p = -1.96$ V) has no effect on the first redox couple for $CrCl_3$ ($\Delta E = 0.86$ V). The separation in reduction potentials is well outside the range normally associated with redox catalysis ($\Delta E = 0.5$ V). In other combinations ($CrCl_3$ in the presence of **1a** and **1b**) the reduction peaks of the components are too close properly to observe the effect on reversibility of the first wave for $CrCl_3$. However, preparative-scale reduction was carried out, using $CrCl_3$ as mediator, at the foot of the $CrCl_3$ reduction wave (see below). For the tetrabromide **1c** $\Delta E = 0.42$ V and in this case cyclic voltammetry of $CrCl_3$ in the presence of **1c** shows an irreversible first wave, of increased peak height, consistent with redox catalysis.

It is reported[22] that cyclic voltammetry of $Cr^{III}(acac)_3$ (acac = acetylacetonato) gives three cathodic waves with the first one reversible only in the presence of a 40-fold excess of Me_4N(acac). It was proposed that dissociation is coupled to electron transfer (Scheme 1).

We find that cyclic voltammetry of $Cr^{III}(acac)_3$, at 0.2 V s^{-1} gave two reduction peaks, at -1.84 M and -2.2 V (*vs.* SCE). The first peak (R_1) remained irreversible at increased scan rates, but the second peak (R_2) was reversible at 0.5 V s^{-1}. It



Scheme 1 Probable reduction sequence for $C^{III}(acac)_3$.

is most likely that R_1 corresponds to the one-electron reduction of $Cr^{III}(acac)_3$ with subsequent dissociation and R_2 to the reduction of $Cr^{II}(acac)_2$. In the presence of increasing aliquots of **1d**, or of **1e**, the peak current at R_1 increases and the peak for R_2 disappears; under these conditions $i_p/v^{1/2}$ is not independent of the scan rate v. Consequently it seems possible that reduction of the precursors **1d**, and **1e**, is mediated by reduction of $Cr^{III}(acac)_3$ and that homogeneous electron transfer outruns dissociation of $Cr^{II}(acac)_3$.

The effectiveness of Ni^{II}(salen) and of Co^{II}(salen) as mediators for the reduction of organic halides has been well demonstrated.[11,12,23] In agreement with this we find that, in DMF solution, both complexes give reversible one-electron reduction peaks (to Ni^I and Co^I respectively) that become irreversible with a concomitant increase in current in the presence of **1d** and **1e** [for Ni^{II}(salen)] and **1c** and **1f** [for Co^{II}(salen)]. In each case the normal independence of $i_p/v^{1/2}$ on scan rate v is lost. It is noteworthy that we found no cyclic voltammetric, or preparative, evidence for interaction between the complexes in their reduced state and 1,3-bis(bromomethyl)benzene, the isomer that cannot form a quinodimethane by reductive elimination.

Preparative-scale electrolysis: "external" mediation by transition metal complexes

The cyclic voltammetric experiments suggested that in several cases quinodimethane formation, and hence complexes of Cr^{III}, Ni^{II}, and Co^{II}, might usefully mediate polymerisation. The results of preparative experiments based on the cyclic voltammetric observations are summarised in Table 2. In order to minimise the possibility of direct rather than mediated reduction the co-electrolysis of metal complex and 1,4-bis(halomethyl)arene was carried out at a potential corresponding to the foot of the first reduction wave of the (more easily reduced) metal complex.

The co-electrolyses (under nitrogen) were preceded by pre-electrolysis of the electrolyte and then prior reduction of the catalyst, in each case to 1 F, and the cell current dropped to the background value. Electrolysis was continued after addition of the 1,4-bis(halomethyl)arene until passage of the charge necessary to convert the whole amount of precursor into polymers, 2 F for PPXs and 4 F for PPVs. The concentration of the catalyst was either *ca.* 0.017 M or 0.03 M and the mediator : substrate ratio was between 1 and 0.1. For details see the Experimental section and footnotes to Table 2.

For the "batch procedure" experiments with a high ratio of mediator to substrate (>0.5) the solution of the reduced complex changed colour when the substrate was introduced. This is strong evidence that homogeneous electron transfer takes place.

Table 2 Polymer formation by indirect electrolysis[a] using transition metal complex mediators

1,4-Bis(halomethyl)arene	ΔE_p(red)/V	Mediator	Mediator : substrate	$-E$(red)[b]/V *vs.* Ag wire	Yield[c] (% PPX)
1a	0.10	$CrCl_3$	0.1	0.8	100
1b	0.24		0.25	0.9	82
1c	0.42		1.0	1.0	100(PPV)
	0.22	Co(salen)	0.5	1.1	Not determined
1d	0.86	$CrCl_3$	0.5	1.2	0
	0.12	$Cr(acac)_3$	0.5	1.35	30
	0.29	Ni(salen)	0.5	1.4	50
1e	0.19	$Cr(acac)_3$	0.5	1.35	42
	0.36	Ni(salen)	0.5	1.4	83[c]

[a] Hg pool cathode, divided cell, DMF–Bu_4NBF_4 (0.1 M). [b] For the second part of the electrolysis; see Experimental section for the relationship between Ag wire and SCE reference electrodes. [c] Not optimised.

Table 3 Mediation *via* an anthranilic acid complex

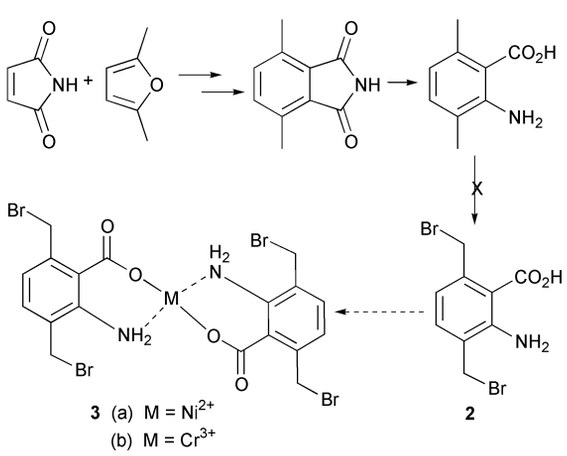
Components	$-E_p$/V *vs.* SCE[a]	Comment[b]
Anthranilic acid (2-aminobenzoic acid)	1.74	
$CrCl_3 \cdot 6H_2O$	1.1	
Anthranilic acid (3 equiv.) + $CrCl_3 \cdot 6H_2O$	1.33	E_p(ox) = +0.58 V
Anthranilic acid (3 equiv.) + $CrCl_3 \cdot 6H_2O$ + **1f** (2.3 equiv.)	1.30; 1.1[c]	PPV formed in 76% yield

[a] Hg/Pt cathode, DMF–Bu_4NBF_4 (0.1 M). 0.2 V s^{-1}. [b] See text for further explanation. [c] Two-stage electrolysis according to procedure described in text.

In one case that was attempted, a good preparative result was obtained with the mediator in *ca.* 10 mol%.

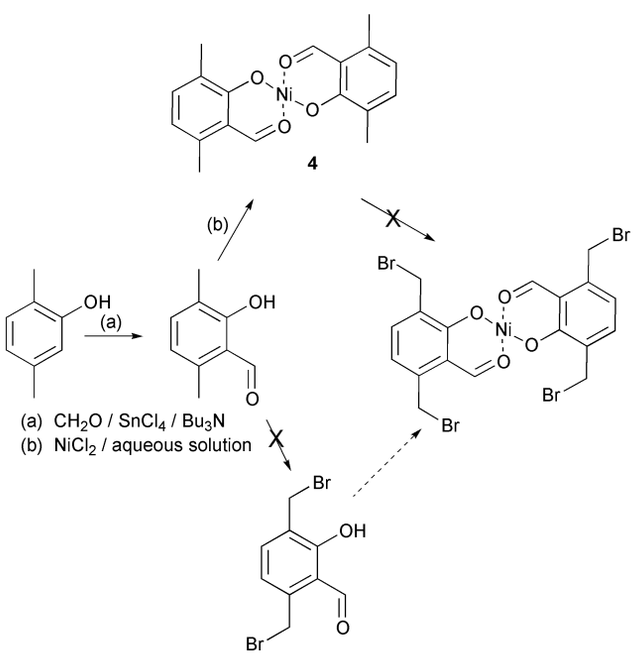
Electrogeneration of PPX polymers *via* QDMs formed by intramolecular redox catalysis (homomediation)—proof of concept

The incorporation in the same molecule of the quinodimethane precursor functionality (the 1,4-bis(halomethyl)arene) and a complexed transition metal offers the possibility for formation of polymers/oligomers with included metals. A candidate was the anthranilic acid derivative **2**, and preparation was unsuccessfully attempted by the route[24,25] shown in Scheme 2, in the expectation that the nickel complex **3a** would ultimately be formed. A Cr(III) complex of anthranilic acid has been reported.[26,27] The likelihood that an anthranilic acid complex would work, in this case involving Cr(III)/Cr(II) was indicated by the experiments summarised in Table 3. Anthranilic acid is less easily reduced than $CrCl_3 \cdot 6H_2O$ in DMF; reduction of the Cr(III) salt in the presence of anthranilic acid results in the disappearance of the $CrCl_3 \cdot 6H_2O$ peak and the appearance of two new peaks, a reduction at −1.33 V and an oxidation at +0.58 V. We propose that the peak at −1.33 V is due to the *in situ* formation of a Cr(III) complex analogous to **3b**, based on literature precedent,[26,27] although we failed to isolate it. However, the complex formed in solution nicely mediates quinodimethane and hence polymer formation, as shown by the co-electrolysis with **1f** to give PPV (Table 3).



Scheme 2 Attempted route to anthranilic acid complex as potential mediator.

By analogy salicylaldehyde derivatives form complexes that should mediate reductive cleavage in our systems; indeed bis-(salicylaldehydato)nickel(II) dihydrate and the corresponding Co(II) complexes have been much studied.[28,29] The route in Scheme 3 describes the attempted preparation of a possible precursor of the type of complex required, but the high reactivity to electrophilic substitution resulted in ring rather than side-chain bromination in the final step. However, the nickel complex **4**, closely analogous to diaquabis(salicylaldehydato-*O*,*O*′)nickel,[28] was prepared as orange–red crystals and characterised by ^{1}H NMR.



Scheme 3 Synthesis of the bis(dimethylsalicylaldehydato)nickel(II) dihydrate mediator **4**.

Cyclic voltammetric and preparative electrolysis results

Table 4 Mediation *via* a salicylaldehyde complex[a]

Component	$-E_p$ or $-E°$/V *vs.*SCE	Comment
Salicylaldehyde	1.33	Reversible
Bis(salicylaldehydato)cobalt(II) dihydrate	1.60; 1.91	Irreversible
4	1.76	Reversible
4 (10 mol%)[b] + **1d** (coelectrolysis)	$E_{red} = -1.45$	61% corresponding PPX
4 (20 mol%)[b] + **1d** (coelectrolysis)	$E_{red} = -1.45$	75% corresponding PPX
4 (10 mol%)[b] + **1e** (coelectrolysis)	$E_{red} = -1.50$	70% corresponding PPX
4 (20 mol%)[b] + **1e** (coelectrolysis)	$E_{red} = -1.50$	75% corresponding PPX

[a] Hg/Pt or Hg pool cathode, DMF–Bu_4NBF_4 (0.1 M), CV at 0.2 V s^{-1}. [b] The mediator was recovered in 70–98% yield.

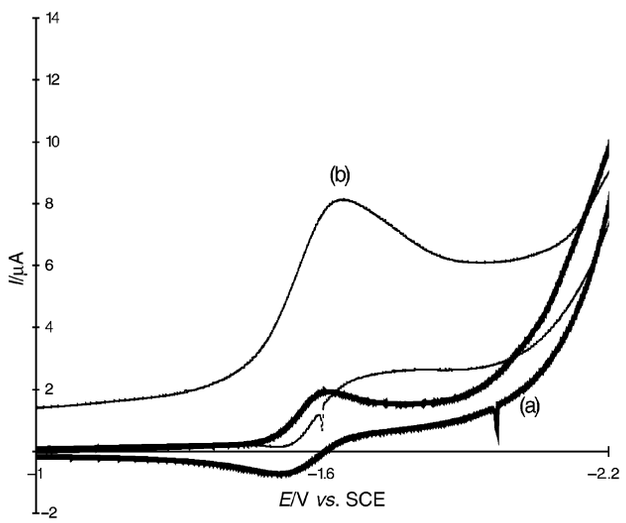


Fig. 1 Cyclic voltammetric evidence for redox catalysis in reduction of catechol derivative **7** (Scheme 4); Au cathode, DMF–Et_4NBr (0.1 M), 0.3 V s^{-1}; (a) Ni(salen), 1.16 mM, (b) as for (a) +**7**, 0.82 mM.

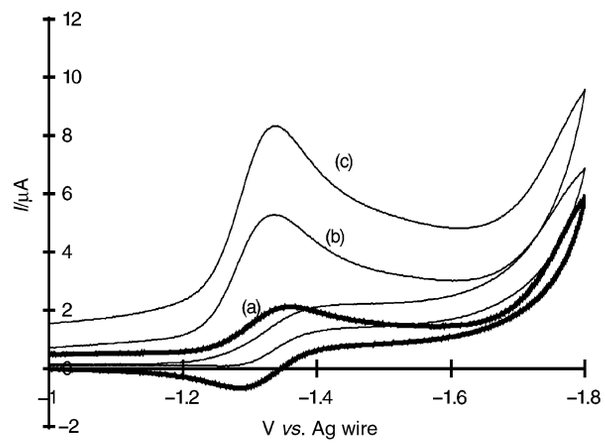
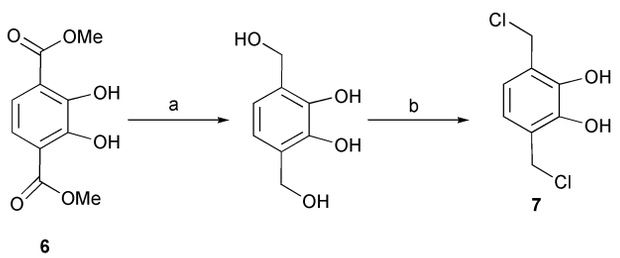


Fig. 2 Cyclic voltammetric evidence for redox catalysis of reductive cleavage of compound **26** (Scheme 7); Hg/Pt cathode, DMF–Et_4NBr (0.1 M), 0.1 V s^{-1}; (a) Ni(salen), 0.9 mM, (b) as for (a) +**26**, 1.1 mM, (c) as for (a) +**26**, 2.8 mM.

concerning salicylaldehyde complexes are summarised in Table 4. Essentially, the complexes are less easily reduced than salicylaldehyde. Bis(salicylaldehydato)cobalt(II) dihydrate,[29] in DMF, is reduced irreversibly whereas the Ni(II) complex **4** reduces reversibly at a potential suitable for mediation of reductive cleavage of substrates **1d** and **1e**. This is confirmed by efficient preparative conversions into the corresponding PPXs. Although the analogue of **4**, containing a 1,4-bis(bromomethyl) function, could not be prepared, the results encouraged further attempts at demonstrating "homomediation".

The electrochemical conversion of a catechol-based precursor was also explored because these are known[30] to complex metal ions, especially Fe(III). The compound **7** was prepared according to Scheme 4 (see also Scheme 6) and examination of



a. $LiAlH_4$/THF, 0 °C (2h), rt (2h); b. $SOCl_2/CH_2Cl_2$, rt (2h)

Scheme 4 (see also Scheme 6). Route to model compound **7**.

its electrochemistry was encouraging. Compound **7** shows an irreversible reduction peak at −1.90 V (*vs.* SCE) [Pt/Hg cathode, DMF–Et_4NBr (0.1 M), 0.2 V s^{-1}]. Co-electrolysis with the more easily reduced Ni(II)salen shows evidence of redox catalysis (Fig. 1) and two-stage preparative electrolysis (prior 1 F reduction of Ni(II)salen, addition of **7** and further 2 F reduction) gave, after work up and isolation by centrifugation, a small amount (<50%) of a brown solid containing no C–Cl groups (by FTIR) and giving broad signals in the ^1H NMR spectrum. Examination by gel permeation chromatography gave a bimodal distribution with high and low molecular weight bands in the peak area ratio of 32 : 1. The broad high molecular weight band gave $M_n = 1.3 \times 10^6$ with a polydispersivity of 17. Hence we can conclude that catechol-based polymers can be formed by mediated electrolysis but that improvement of the route to the precursors is necessary before more progress can be made, including the incorporation of metals into the precursors or into the polymers.

An alternative, but less straightforward approach is separately to design the ligand and the QDM precursor function and to link them by an electrochemically inert bridge. Consequently compound **23** (see Scheme 6) was chosen as a target, because the 1,4-bis(chloromethyl)arene and the salen-like ligand could be linked using well-tried macrocycle synthetic methodology. The successful route is outlined in Schemes 5 and 6 and full details are given in the Experimental section; during the final stages of the sequence part of the product had complexed with sodium, which was detected by electrospray mass spectrometry. At an early stage it was necessary to establish that the chosen metal complex (essentially Ni(II)salen) would indeed mediate reductive cleavage of the 1,4-bis(chloromethyl)-3,4-dialkoxyarene unit. The cyclic voltammogram in Fig. 2 involving the model compound **26** (Scheme 7) indicates clearly that the expected redox catalysis is observed.

Realisation of intramolecular redox catalysis (homomediation)

The macrocyclic ligand **22** (and the corresponding sodium complex) was readily converted by reaction with nickel acetate in methanol into the corresponding nickel complex and then into **23**, which was well characterised by NMR and by electrospray mass spectrometry. Preparative electrolysis, at 0.013 M

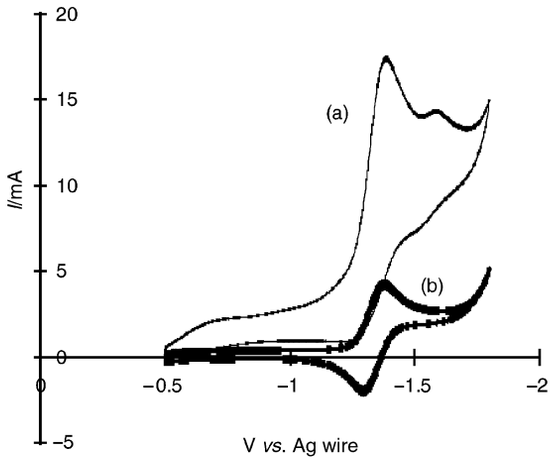


Fig. 3 Cyclic voltammograms during preparative electrolysis of macrocycle **23** (Scheme 6); [0.013 M, Hg/Pt cathode, DMF–Et_4NBr (0.1 M), 0.5 V s^{-1}], (a) before electrolysis, (b) after 2 F electrolysis.

substrate concentration, was monitored by cyclic voltammetry and the outcome is summarised in Fig. 3. Initially a substantial reduction current [Fig. 3, curve (a)] is observed with little reverse oxidation, which is consistent with electrolysis involving redox catalysis. At the conclusion of electrolysis (2 F) a residual redox couple [Fig. 3, curve (b)] is observed that is due to the nickel complex bound into the oligomeric/polymeric product. [*N.B.*, because of the high concentration used in the cyclic voltammetric monitoring, it is not easy to compare peak currents, and hence diffusion coefficients, for Ni(II)salen (Fig. 2) and the Ni(II) species in the macromolecule/oligomer.]

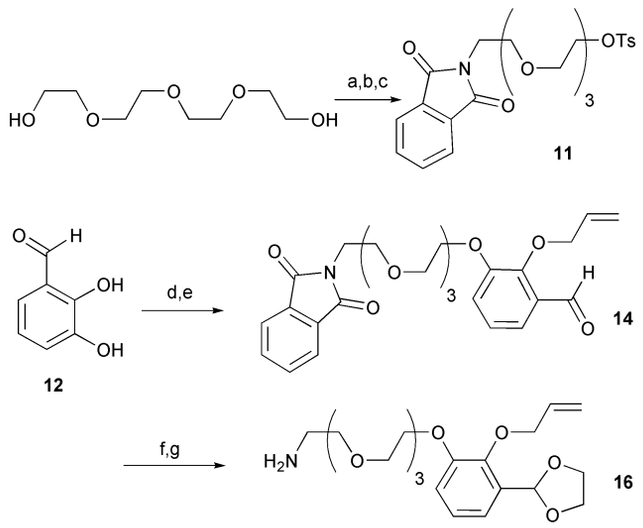
The observed E^0 value is the same as that for Ni(II)salen, which is understandable as the Ni(II) environment in the macrocycle is very similar to that in Ni(II)salen. The product of electrolysis, obtained in 85% yield, was characterised by ^{13}C NMR spectroscopy, FTIR, electrospray mass spectrometry and atomic absorption spectroscopy. The last technique revealed that the nickel content was 66% of the theoretical maximum occupancy. The remaining sites could well be occupied by Na^+, which is prevalent in these systems and for which we did not test.

We have chosen to depict the electrochemical conversion of compound as intramolecular with homogeneous electron transfer from Ni(I) being preferentially across the macrocycle (homomediation). This is based on the proximity of the nickel atom to the edge of the arene unit; MM2 energy minimisation of the structure **23** gives a preferred conformation in which the intramolecular separation of the nickel atom and arene unit is *ca.* 12 Å. For comparison, for a recently studied[20] case of intramolecular dissociative electron transfer, the distance between the arene (donor) groups (centre of the ring) and the frangible acceptor group (C–Br) in the 4-aroyloxy-1-methylcyclohexyl bromides is about 6 Å. In our system the size and polarity of the macrocycle will result in a relatively low diffusion coefficient that in principle should discriminate against outer sphere electron transfer by bimolecular reaction. Furthermore, intramolecular inner sphere electron transfer is sterically inhibited and it is unlikely, also for steric reasons, that two of these macrocycles could combine to effect intermolecular inner sphere electron transfer.

Synthesis of the macrocyclic complex 23 and its precursors

The multistage convergent synthesis of **23** requires separate description and explanation. The key steps are given in outline, and reagents and conditions summarised, in Schemes 5 and 6.

Direct halogenation of both methyl groups of either 3,6-dimethylanthranilic acid or 3,6-dimethyl-2-hydroxybenzaldehyde into the corresponding chloro- or bromomethyl derivatives failed (Schemes 2 and 3) and complexation of the

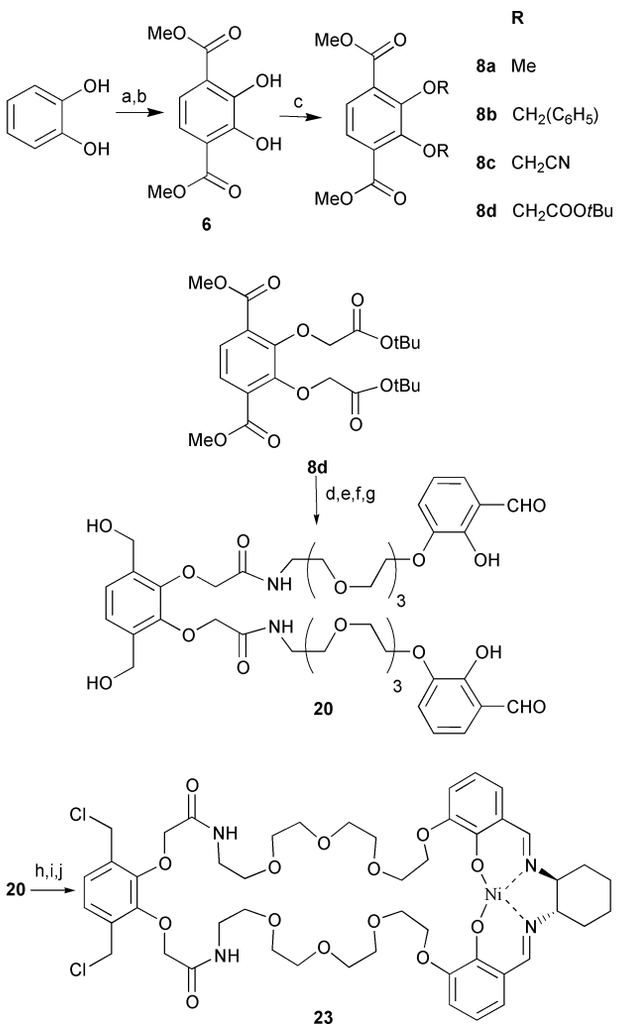


Scheme 5 Assembly of the amine **16**: a) TsCl, Et_3N, DMAP, CH_2Cl_2, rt, 18 h, 75% (**9**); b) K phthalimide, DMF, 100 °C, 8 h, 84% (**10**); c) TsCl, Et_3N, DMAP, CH_2Cl_2, rt, 18 h, 64% (**11**); d) NaH, allyl bromide, DMSO, rt, 50% (**13**); e) (**11**), K_2CO_3, MeCN, reflux, 48 h, 83% (**14**); f) $(CH_2OH)_2$, TsOH, $CH(OMe)_3$, toluene, reflux, 8 h (**15**); g) N_2H_4, MeOH, reflux, 5 h, 79% (**16**).

anthranilic group with Ni or Co prior to halogenation was problematical. An alternative synthetic strategy was developed to obtain a molecule, which has both the desired bis(chloromethyl) functionality as well as a chelated transition metal atom, the latter acting as a mediator in the electroreduction. Chloromethyl groups are incompatible with the nucleophilic properties of most of the metal-chelating ligands of interest. Direct chlorination (Cl_2, NCS) is too harsh and likely to result in competing ring-substitution, which immediately excludes 1,4-dimethyl groups as precursors to the chloromethyl functions. The reduction of methoxycarbonyl groups was therefore explored with, after the incorporation of the transition metal, conversion of the resulting hydroxymethyl groups into chloromethyl groups using mild substitution methods. This sequence was chosen to avoid complications from the reactions of probably labile chloromethyl transition metal complexes during work up and purification. We have shown the salen metal-chelating function to be a good mediator for bis(chloromethyl)-arenes, while a host of different metals, *e.g.* Ni(II), Co(II), Zn(II), Cu(II), are known to complex to give planar diamagnetic complexes. The synthesis of macrocyclic salens has been described in literature;[31] if the salen- and the bis(chloromethylarene) unit are incorporated in a common macrocycle, the resulting PPX materials produced by electrolysis or coelectrolysis should be capable of complexing a variety of metal cations.

Synthesis of macrocyclic salen 23

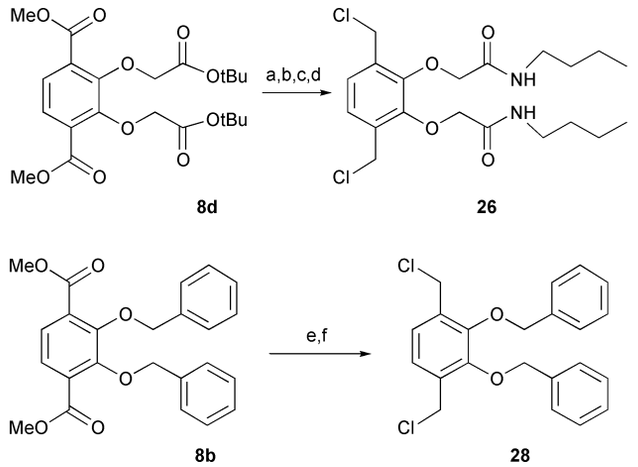
A convergent synthetic route was designed in which a 1,4-disubstituted catechol would serve as a progenitor both to a 1,4-bis(chloromethylarene) intermediate and a symmetrical linker for macrocycle construction. The overall route is set out in Schemes 5 and 6. Catechol was bis-carboxylated to give compound **5** using a Kolbe–Schmitt carboxylation procedure.[32,33] The dimethyl ester **6** was obtained in 65% yield by esterification of the crude acid in refluxing methanol using sulfuric acid as a catalyst. Surprisingly, alkylation of both phenolic hydroxy groups, using K_2CO_3 as a base and methyl, ethyl and propyl bromides or iodides as electrophiles, failed even after prolonged reflux. The lower reactivity of the phenolate anion is probably due to steric hindrance by the *o*-methoxycarbonyl groups. However, using more reactive alkylating agents such as dimethyl sulfate and benzyl bromide gave the corresponding dimethylated and dibenzylated catechols **8a** and **8b**, respectively. Similarly both bis(cyano-



Scheme 6 Assembly of the proteced catechol and convergence to the macrocycle **23**: a) 1) NaOH, MeOH, rt; 2) 110 °C, 3 days; 3) CO_2, 70 bar, 200 °C, 2 days, 40% (**5**); b) MeOH, H_2SO_4, reflux, 8 h, 65% (**6**); c) K_2CO_3, MeCN, RX, reflux, 18–48 h, 70–95% (**8a**–**d**); d) CF_3COOH, rt, 3 h, 100% (**17**); e) 1) $SOCl_2$, reflux, 1 h; 2) (**16**), Et_3N, DMAP, CH_2Cl_2, 0 °C–rt, 74% (**18**); f) 1) $LiAlH_4$, THF, 0 °C to rt, 2 h; 2) H^+, 99% (**19**); g) $Pd(OAc)_2$, $P(C_6H_6)_3$, Et_3N, HCOOH, EtOH–H_2O, reflux, 1.5 h, 62% (**20**); h) (±)-*trans*-cyclohexane-1,2-diamine, $Ba(OTf)_2$, THF, reflux, 50% (**21**); i) $Ni(OAc)_2$, MeOH, 1 min, 95% (**22**); j) MsCl, Et_3N, $CHCl_3$, 55 °C, 6 h, 95% (**23**).

methyl) and bis(*tert*-butoxycarbonylmethyl) derivatives (**8c** and **8d**) could be prepared in good yields (70–95%). Hydrogenation of the cyano groups of **8c** failed to give aminomethyl compounds, probably due to partial amidation of the methyl esters. However, quantitative selective hydrolysis of the *tert*-butyl esters of **8d**, in the presence of methyl esters, was achieved in anhydrous TFA at room temperature, yielding the diacid **17**, which proved to be a useful intermediate. The proposed synthetic procedure was partly tested by the prior synthesis of model compound **26** (Scheme 7), which represents the bis-(chloromethyl) part of the target molecule. Diacid **17** was reacted with $SOCl_2$, to give the corresponding di-acid chloride.

Subsequent amidation with *n*-butylamine gave **24** in 84% yield, using chilled CH_2Cl_2 as a solvent and triethylamine–DMAP as a base–catalyst system. Selective reduction of the more reactive methyl esters in **24** in the presence of amide groups was achieved with $LiAlH_4$ at room temperature. After work-up the bis(hydroxymethylated) diamide **25** was obtained in 71% yield. The hydroxymethyl groups of **25** were converted into chloromethyl groups by reaction with $SOCl_2$–2,6-lutidine. Alternative chlorination methods were tested with similar results. These results and the similar preparation of bis-(chloromethylated) compound **28** (Scheme 7), starting from



Scheme 7 Preparation of model compound **26** and **28**: a) CF_3COOH, rt, 3 h, 100% (**17**); b) 1) $SOCl_2$, reflux, 1 h; 2) *n*-$BuNH_2$, Et_3N, DMAP, CH_2Cl_2, 0 °C–rt, 84% (**24**); c) 1) $LiAlH_4$, THF, 0 °C to rt, 2 h (**25**); 2) H^+, 71%; d) $SOCl_2$, 2,6-lutidine, rt, 1 h, quantitative (**26**); e) 1) $LiAlH_4$, THF, 0 °C to rt, 2 h; 2) H^+, quantitative (**27**); f) $SOCl_2$, CH_2Cl_2, reflux, 1 h, quantitative (**28**).

bis(benzylated) diester **8b**, gave confidence in the particular synthetic route towards this new class of compounds.

The planned synthesis of macrocycle **23** (Scheme 6) involved linking two formyl-substituted catechol units to the diacid **17** *via* tetraoxyethane spacers with subsequent reduction of the methyl esters to hydroxymethyl groups. The closure to a macrocycle required the condensation of both *o*-hydroxyformyl groups with an appropriate diamine to produce the desired salen functionality. Using Ba^{2+} as a template ensured proximity of the formyl groups. After metallation of the salen, the hydroxymethyl groups could be converted into chloromethyl groups, thus completing the synthesis.

The mono-tosylated glycol **9** was prepared by reaction using a two-fold excess of tetraethylene glycol and DMAP as a catalyst, and isolated in 75% yield by column chromatography. The protection of the amine was achieved by substitution with phthalimide in hot DMF to give **10** (84% yield). Subsequent tosylation of the remaining hydroxy group, using a procedure similar to that giving **9**, gave **11**.

2,3-Dihydroxybenzaldehyde (**12**) was the starting material for synthesis of the intermediate amine **16** (Scheme 5). Selective allylation of the more nucleophilic (and less acidic) *o*-hydroxy group was achieved by double deprotonation, using 2.2 equiv. of NaH in DMSO, and reaction with 1 equiv. of allyl bromide.[31] The unprotected 3-hydroxy group was combined with the tosyl-phthalimide **11** in MeCN–K_2CO_3 (**14** in 83% yield after purification). The formyl group of **14** was protected as a dioxole ether (**15**, quantitative yield) by acid-catalysed condensation with glycol and efficient water removal (toluene–trimethyl orthoformate). Deprotection by removal of the phthalimide group with a methanolic solution of hydrazine was straightforward and gave the amine **16** (79%).

Synthesis of precursor **20** (Scheme 6) started from the *tert*-butyl ester **8d** following the methodology described earlier for the preparation of **26**; thus conversion of **16** into the bisamide **18** was achieved (74%). The methyl ester groups of **18** were successfully reduced ($LiAlH_4$–THF) and acidic work-up hydrolysed the dioxole groups to give **19** in almost quantitative yield. Finally, palladium catalysed reductive deallylation (*in situ* palladium tetrakis(triphenylphosphine)) gave **20** (62%). The progress of this reaction was monitored carefully by TLC, as both purity and yield are adversely affected by prolonged reaction times.

Ring closure of **20** was achieved by first adding $Ba(OTf)_2$ to a dilute, refluxing solution of **20** followed by addition of *trans*-cyclohexane-1,2-diamine. Purification by column chromatography gave two major fractions in a total yield of 50%.

^{1}H NMR spectroscopy and mass spectrometry indicated that one fraction was the free ligand (**21**) whereas the other was a sodium complex (see below). The macrocycle **21** was reacted with nickel(II) acetate in methanol to give **22** and the synthesis completed by conversion of the hydroxymethyl groups of compound **22** into chloromethyl groups to give **23** (Scheme 6). Alternative procedures using $SOCl_2$ failed due to partial hydrolysis of the nickel salen unit. As anticipated, the macrocyclic salen complex **23** could not be purified by column chromatography.

Characterisation of the macrocycles

The free ligand, **21**, exhibits a complex ^{1}H NMR spectrum. Multiple signals are present for both the hydroxymethyl groups and the methylene protons of the carbamoylmethoxy units. The resonance at $\delta = 13.5$ ppm (phenolic OH group of the salen unit) indicates strong hydrogen bonding to the imine nitrogen. Two main fractions were isolated from the chromatographic purification of **21**. Both fractions gave a clear electrospray mass spectrum, each showing molecular ion signals at *m*/*z* 955.5 for the protonated species (calculated 954.5) and at 977.4, for the sodium complex. Reacting each fraction separately or alternatively reacting the mixture of both fractions of **21** with nickel(II) acetate gave a product with a greatly simplified ^{1}H NMR spectrum corresponding to that of a single compound with high symmetry. Hence, the two fractions of **21** are the empty macrocycle and its sodium complex. The complexity of the ^{1}H NMR spectrum of **21** is most likely governed by hydrogen bonding involving interaction between the hydroxymethyl groups or the amide groups and the phenolic oxygens. This hydrogen bonding is effectively inhibited upon complexation with Ni(II). The chloromethylated compound **23** was characterised by ^{13}C NMR spectroscopy and electrospray mass spectroscopy. The latter showed the molecular ion pattern of the empty macrocycle at *m*/*z* 1046 and its sodium complex at 1069. The observed multiple signals are due to the isotope distribution of nickel, chlorine and sodium and excellently matched the calculated distribution. The PPX type polymer obtained after electrolysis of **23** gave broad signals in the ^{1}H NMR. The presence of highly symmetrical macrocyclic units, however, could be deduced. Similar results were obtained from the ^{13}C NMR spectrum, which clearly showed the presence of all major signals, with the exception of those for the chloromethyl groups. The methylene signal at $\delta = 30.4$ and the methyl signal at $\delta = 16.6$ clearly show the formation of oligomeric material. From quantitative ^{13}C NMR spectroscopy, using an inverse gated pulse sequence with a delay time of 20 s, an average oligomerisation degree of 2 to 5 was calculated. Electrospray mass spectrometry confirmed the presence of monomer and its sodium complex at *m*/*z* 979 and 1001, respectively. A weak dimer signal was observed at 1980 (Na complex) and a complex signal pattern between 480 and 580. Firm conclusions with respect to the degree of oligomerisation cannot be obtained from electrospray mass spectrometry as the polymer forms a poly-sodium complex, whose signal position depends on the *m*/*z* ratio. As the sodium charge of the oligomers is not well defined, oligomers with, for example, a single Na-ion per macrocyclic unit will show a signal at around *m*/*z* 1000, those with two sodium ions per macrocyclic unit will exhibit a signal at around 512, while a dimer with three Na-ions has a signal at 675. However, the presence of a complex signal pattern between 480 and 580 indicates the material to be of a poly-sodium loaded oligomeric nature.

Experimental

Materials and general procedures

For preparative electrolyses DMF (Aldrich) was used without further purification. For cyclic voltammetry and controlled potential coulometry DMF (Aldrich, HPLC grade) was used and stored over freshly-baked (150 °C) 4 Å molecular sieves, as was acetonitrile. Supporting electrolytes (Aldrich) were used without further purification. Dry CH_2Cl_2 was distilled from P_2O_5. THF was distilled from K-metal with added benzophenone as an indicator. All other solvents were analytically pure and were used without further purification. Petroleum ether refers to the fraction with bp 60–80 °C. All reactions were carried out under a N_2-atmosphere.

Melting points were determined on an Electrothermal capillary tube melting point apparatus and were uncorrected. Infra red spectra were recorded on KBr discs using a Perkin-Elmer 1600 series FTIR spectrophotometer. ^{1}H NMR spectra and ^{13}C NMR spectra (63 MHz) were measured on a Bruker AM 250 (250 MHz) spectrometer. Solid-state ^{13}C NMR spectra were recorded at 75 MHz on a Bruker MSL-300 multinuclear NMR spectrometer of the University of London Intercollegiate Research Service (ULIRS). EI mass spectra and direct pyrolysis mass spectra were measured using a Kratos MS50RF/Kratos-DS90 data system; FAB mass spectra were obtained on the same spectrometer using *m*-nitrobenzyl alcohol or glycerol as a matrix.

Preparative-scale column chromatography separations used Merck silica gel 60H (230–400 mesh) and pre-coated silica gel plates (Merck, 60 F_{254}) were used for analytical TLC.

HPLC experiments were carried out using a Hewlett Packard HP1100 Series Liquid Chromatograph with UV detection at 270 nm. The instrument was equipped with a Zorbax Sil column (5 μm, 4.6 mm id × 250 mm) and guard, run isocratically with EtOAc–hexane (30 : 70%, Merck HPLC grade) eluent at 1.0 ml min^{-1} and an injection volume of 10 μl.

Gel permeation chromatography: a Hewlett Packard HP1100 series liquid chromatograph, operated by HP ChemStation software, was employed with a quaternary gradient pump and UV (270 nm) detector. Polymer molecular weights were calculated using a Polymer Laboratories PL caliber GPC system, version 4.01. Polymer Laboratories PL-gel [poly(styrene–divinylbenzene) copolymer gel] mixed C (5 μm), two 300 × 7.5 mm and guard columns, enclosed in a constant temperature oven, were used. A calibration curve was constructed using narrow standard poly(styrene) (molecular weight range 500 to 3×10^6). The mobile phase was DMF (Aldrich, HPLC grade) containing 0.1% LiBr at 73 °C and at the elution rate of 1.0 ml min^{-1}

Atomic absorption measurements: about 12 mg of the metal-containing polymer sample were accurately weighed and dissolved in 10 ml of concentrated nitric acid (AR, 69%). The extract was diluted to 100 ml using distilled water, to give a final acid concentration of about 10% v/v. A blank was also prepared using the same reagents. Immediately prior to analysis the samples were filtered through a Whatman 541 filter paper to remove particulate carbon. The metals were determined by atomic absorption spectroscopy using a Unicam 939 AAS with an air–acetylene flame. Standards were prepared by diluting Spectrosol (BDH) 1000 ppm standard solutions of nickel with subsequent dilution. Nickel was measured at 232.0 nm with background correction. No nickel was found in the blank samples.

Electrochemical experiments

Cyclic voltammetric experiments were performed using either a Princeton Applied Research (PAR) VersaStat or Model263A potentiostat with controlling PAR software (Model 270/250 Research Electrochemistry Software v 4.00). Glass cells for cyclic voltammetry were undivided and equipped with an Au disc (1 mm) or a mercury-coated platinum disk (0.1–0.6 mm) working electrode (cathode), Ag-wire reference electrode and platinum coil counter electrode (anode). The experiments were typically carried out in DMF–Et_4NBr (0.1 M) solution. The

concentration of the substrate was 1–3 mM and the scan rate varied from 0.1–200 V s^{-1}. Because the potential of the Ag wire reference electrode can vary over a relatively short timescale, the E^0 value for anthracene was normally measured at the beginning and at the end of a series of measurements, against the Ag wire electrode, so that reduction potentials could be consistently referred to the SCE electrode (E^0 for anthracene = −1.92 V *vs*. SCE in DMF [34]).

Preparative scale electrochemical reductions were performed using conventional glass cells, with the anode and cathode compartments separated by a glass sinter. The cells were equipped with a mercury pool working electrode (cathode), a Ag-wire reference electrode and a carbon rod counter electrode (anode). Reduction potentials for controlled potential electrolyses were determined by cyclic voltammetry on the solutions immediately prior to electrolysis, *i.e.* at greater than ideal concentrations. Consequently the peak potentials so determined, against the relatively unstable Ag wire reference, serve to enable reduction at the first reduction wave in an electrolysis immediately following measurement. However, actual values fluctuate from day-to-day and cannot be compared with peak potentials measured at low concentration with reference to SCE (see above). The reactions were kept an under an inert atmosphere by the slow bubbling of dry nitrogen through the electrolytes. The catholyte was mechanically stirred.

Controlled potential electrolysis: in a divided cell at an Hg pool cathode the electrolyte was pre-electrolysed at the potential to be used. The mediator was then electrolysed until consumption of the required amount of charge (1 F) occurred and the cell current dropped to the background value. The substrate was introduced and a second electrolysis carried out as far as it was necessary to convert the whole amount of precursor into polymers (2 F for PPXs and 4 F for PPVs). The mediator concentration was in the range 0.017 to 0.03 M and the concentration of the starting materials was between 1 and 10 equivalents in relation to the mediator concentration. The working electrode, a mercury pool (5 or 10 cm^2), was continuously stirred not only to improve mass transport but also to preclude the covering of the electrode by polymer. Insoluble polymer product was removed by filtration, washed with water and dried. Dilution of the catholyte with weak aqueous HCl caused precipitation of DMF-soluble product.

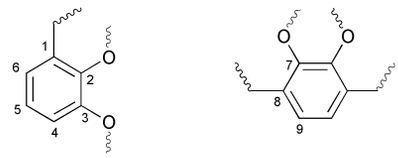
Polymers were characterised by FTIR or ^{1}H NMR spectroscopy (when soluble in organic solvents). Characteristic absorptions are well documented:[3,35] PPXs (ν/cm^{-1}): 3044 (aromatic C–H), 2920 (sat. C–H), 1510 (benzene ring) and 821 (two adjacent H on benzene ring); PPVs (ν/cm^{-1}): 3013 (aromatic C–H), 1595 and 1510 (benzene ring), 961 (*trans*-H–C=C–H) and 825 (two adjacent H on benzene ring).

Starting materials

Compounds **5**,[32,33] **6**,[32,33] **8a**, **8b**, 1,4-bis(hydroxymethyl)-2,3-dihydroxybenzene and **9** were prepared according to slightly modified literature procedures, while compound **13** was prepared according to a well established literature procedure.[31] The numbering of carbon atoms for the catechol derivatives described below is given in Scheme 8.

Attempted preparation of 3,6-bis(bromomethyl)-2-aminobenzoic acid (2) [Scheme 2]

3,6-Dimethylphthalimide. Maleimide (3.0 g, 31 mmol) in CH_2Cl_2 (80 ml) was reacted with redistilled 2,5-dimethylfuran (4 ml, 33 mmol). After stirring at room temperature for 30 min $BF_3{\cdot}Et_2O$ (4.3 ml, 35 mmol) was added and the colour of the solution turned dark orange. After 12 h stirring at room temperature the red–brown slurry was neutralised and the organic layer separated and dried over $MgSO_4$. The solvent was reduced to approx. 10 ml and the product precipitated by addition of petroleum ether to give a yellow solid. Yield: 2.1 g (40%); mp 143 °C (petroleum ether); ^{1}H NMR δ 7.8 (br s, 1H, NH), 7.35 (s, 2H, ArH), 2.65 (s, 6H, CH_3); ^{13}C NMR δ 169.1 (s, CO), 136.4, 135.7, 129.6, 17.4 (q, CH_3).



Scheme 8 Numbering of aromatic carbon atoms in catechol derivatives.

2-Amino-3,6-dimethylbenzoic acid. A mixture of calcium hypochlorite (800 mg), potassium carbonate (570 mg) and KOH (160 mg) in approx. 15 ml water was shaken for 5 min, filtered and additional KOH (1.8 g) was added. To the resulting solution 3,6-dimethylphthalimide (1.0 g, 5.7 mmol) was added. After 30 min stirring at 50 °C the solution was carefully acidified with acetic acid to ensure that the pH did not fall below 4. The solution was extracted with diethyl ether (3 × 100 ml). The combined organic layers were dried over Na_2SO_4 and evaporated to give a yellow solid, which was recrystallised from EtOH–H_2O to obtain off-white crystals. Yield: 650 mg (69%); mp 112 °C (EtOH–H_2O); ^{1}H NMR δ (DMSO-d_6) 7.02, 6.44 (d, 1H, J = 6 Hz, ArH), 3.73 (br s, 2H, NH), 2.45, 2.15 (s, 3H, CH_3).

3,6-Dimethylsalicylaldehyde. 2,5-Dimethylphenol (12.2 g, 0.1 mol) was dissolved, under a nitrogen atmosphere, in anhydrous toluene (30 ml). $SnCl_4$ (2.6 g, 0.01 mol) and tributylamine (6.9 ml, 0.01 mol) were added. The resulting yellow solution was stirred for 20 min and paraformaldehyde (6.6 g, 0.22 mol) added. The yellow slurry was heated to 100 °C and kept at that temperature for 8 h. The resulting brown solution was added to water (500 ml) and acidified to pH = 2 with hydrochloric acid. The layers were separated and the aqueous layer extracted with ether. The combined organic layers were washed with brine, dried and the solvent evaporated. The crude product was steam distilled to give a yellow oil that was recrystallised from EtOH to give light yellow crystals. Yield: 10.2 g (68%); mp 62 °C (EtOH); ^{1}H NMR δ 12.17 (s, 1H, OH), 10.32 (s, 1H, CHO), 7.25, 6.72 (d, 1H, J = 8 Hz, ArH), 2.56, 2.22 (s, 3H, CH_3).

Bis(3,6-dimethylsalicylaldehydato)nickel(II) mediator (4). [Scheme 3] Nickel(II) chloride (795 mg, 3.3 mmol) was dissolved in water (10 ml) and 3,6-dimethylsalicylaldehyde (1 g, 6.6 mmol) was added with vigorous stirring. Ethanol was gradually added (maximum 3 ml), until the reactants had dissolved. Aqueous ammonia (0.88 ml) was added until the solution turned from light green to deep orange, then more ammonia (2 ml) was added. The mixture was kept at 50 °C for 1 h. The deep orange product (88% yield) was removed by filtration, washed (water) and dried in a vacuum oven. An aqueous ethanolic solution of the product (*ca.* 10 ml water, 2 ml ethanol) was heated on a steam bath. The solution was concentrated to about half volume and the complex **4** precipitated as a dark orange solid in near quantitative yield. ^{1}H NMR δ 8.3 (s, 1H, OH), 8.08 (s, 1H, CHO), 6.9, 6.25 (d, 1H, J = 8 Hz, ArH), 2.50, 2.25 (s, 3H, CH_3); MS (EI) m/z 359 (M^+, 359).

2,3-Dihydroxyterephthalic acid (5). Catechol (100 g, 0.90 mol) was added portionwise to a methanolic NaOH (73 g, 1.82 mol) solution (500 cm^3). The deep green solution was stirred at room temperature for 18 h and evaporated to dryness. The remaining solid was mortared and dried for three days in a vacuum oven over P_2O_5 at a pressure of 10 mm Hg and a temperature of 110 °C. The tan powder was divided into two portions, each of which was heated for two days in an autoclave under a CO_2 pressure of 70 bar and at a temperature of 200 °C. The resulting greyish powder was stirred in a hot HCl solution (6 M, 2 l) upon which the crude acid precipitated. After cooling to room

temperature, the precipitate was filtered, washed with three portions of water (200 ml) and triturated with a boiling HCl solution (1 M, 2 l). After cooling the solution overnight, the precipitated acid was filtered, washed with water (2 × 200 ml) and dried in a freeze dryer. The brown coloured product was used without further purification. Yield: 40%.

Dimethyl 2,3-dihydroxyterephthalate (6). To a solution of diacid **5** (15.0 g, 75.7 mmol) in MeOH (400 ml) was added 45 ml of concentrated H_2SO_4 (**CAUTION**). The black solution was refluxed for 8 h, cooled to room temperature and kept at −30 °C for 12 h. The black crystalline precipitate was filtered on a sintered glass filter, rinsed with MeOH and dried *in vacuo*. The crude product was used without further purification. Yield: 64%.

General procedure A for the alkylation of dimethyl 2,3-dihydroxyterephthalate (6)

To a suspension of crude diester **6** and three mol equiv. of K_2CO_3 in dry acetonitrile (50 ml g^{-1}) was added the appropriate alkyl halide (2–3 mol equiv.). The mixture was refluxed for 18–48 h. The solvent was evaporated and the residue was taken up in EtOAc. The organic layer was washed with 1 M HCl (1 × 100 ml), brine (1 × 50 ml) and dried over Na_2SO_4. The crude products were purified either by column chromatography (silica gel; mixtures of EtOAc–petroleum ether) or by recrystallisation.

Dimethyl 2,3-dimethoxyterephthalate (8a). 8a was prepared from diester **6** (500 mg, 2.2 mmol), K_2CO_3 (900 mg, 6.6 mmol) and Me_2SO_4 (694 mg, 5.5 mmol). After 48 h of reflux and work-up, the crude product was purified by column chromatography (silica gel; EtOAc–petroleum ether 2 : 3). A light-yellow clear oil was obtained. Yield: 448 mg (80%). ^{1}H NMR δ 7.50 (s, 2H, ArH), 3.95, 3.93 (s, 2 × 6H, COOMe, OMe).

Dimethyl 2,3-bis(benzyloxy)terephthalate (8b). 8b was prepared from diester **6** (2.0 g, 8.84 mmol), K_2CO_3 (3.6 g, 26.4 mmol) and benzyl bromide (4.5 g, 26.4 mmol). After 18 h of reflux and work-up, the crude product was decanted with hot petroleum ether to remove a black tar. Upon filtering and cooling the clear solution, pure **8b** crystallised as a white powder. Yield: 2.24 g (62%). ^{1}H NMR δ 7.54 (s, 2H, ArH), 7.4–7.3 (m, 10H, BnH), 5.12 (s, 4H, CH_2), 3.86 (s, 6H, COOMe); ^{13}C NMR δ 165.9 (s, C=O), 152.8 (s, Ar*C*O), 136.8 (s, Bn*C*), 130.4 (s, ArC), 128.8, 128.5, 128.3 (d, Bn*C*H), 125.7 (d, Ar*C*), 76.6 (t, CH_2), 52.4 (q, OMe).

Dimethyl 2,3-bis(cyanomethoxy)terephthalate (8c). 8c was prepared from diester **6** (500 mg, 2.2 mmol), K_2CO_3 (900 mg, 6.6 mmol), chloroacetonitrile (1.0 g, 13.3 mmol) and a spatula point of NaI. After 24 h of reflux and work-up, the crude product was purified by column chromatography (silica gel; EtOAc–petroleum ether 2 : 3) followed by recrystallisation from MeOH at −30 °C. A greyish crystalline product was obtained. Yield: 380 mg (57%); mp 152–154 °C (MeOH); ^{1}H NMR δ 7.76 (s, 2H, ArH), 4.89 (s, 4H, CH_2CN), 3.98 (s, 6H, OMe); elemental analysis, calcd C, 55.27; H, 3.98; N, 9.20; found C, 53.98; H, 3.73; N, 8.89%.

Dimethyl 2,3-bis[(1,1-dimethylethyl)oxycarbonylmethoxy]-terephthalate (8d). 8d was prepared from diester **6** (11.0 g, 48.6 mmol), K_2CO_3 (20.2 g, 146 mmol) and *tert*-butyl bromoacetate (28.4 g, 146 mmol). After 24 h of reflux and work-up, the crude product was decanted with hot petroleum ether to remove a black tar. Upon filtering and cooling the clear solution to −30 °C, pure **8d** crystallised as pale yellow crystals. Yield: 15.5 g (70%); mp 54–55 °C (petroleum ether); ^{1}C NMR δ 7.55 (s, 2H, ArH), 4.63 (s, 4H, CH_2), 3.91 (s, 6H, COOMe), 1.48 (s, 18H, $C(CH_3)_3$); ^{13}C NMR δ 167.6 (s, CH_2C=O), 165.5 (s, C=O), 151.8 (s, Ar*C*O), 130.2 (s, Ar*C*), 126.0 (d, Ar*C*), 81.8 (s, *C*$(CH_3)_3$), 71.1 (t, OCH_2), 52.5 (q, OMe), 28.1 (q, C(*C*$H_3)_3$); MS (EI) *m*/*z* 454.2 (M^+, 454.2); elemental analysis, calcd C, 58.14; H, 6.65; found C, 58.28; H, 6.65%.

Tetraethylene glycol monotosylate (9). To an ice-cooled solution of tetraethylene glycol (400 g, 354 ml, 2.06 mol), triethylamine (46 g, 62 ml, 0.44 mol) and DMAP (1.0 g) in CH_2Cl_2 (1 l) was added portionwise tosyl chloride (76 g, 0.40 mol). The solution was stirred for 8 h at the same temperature and was then allowed to warm-up to room temperature. After another 10 h stirring, the solution was washed with 1 M HCl solution (2 × 200 ml), water (3 × 300 ml), brine (1 × 100 ml) and dried over Na_2SO_4. Evaporation of the solvent gave a clear oil, which, according to ^{1}H NMR spectroscopy, consisted of approximately 88% of the monotosylated derivative and 12% of the bistosylated derivative. Crude yield: 132 g. Pure monotosylated polyether **9** was obtained by column chromatography of 40 g of crude material (silica gel, gradient elution, EtOAc– petroleum ether 7 : 3 to neat EtOAc). Yield: 28 g (80% recovered). ^{1}H NMR δ 7.77, 7.31 (d, J = 8.3 Hz, 2H, TsH), 4.13 (m, 2H, OCH_2), 3.7–3.5 (m, 14H, OCH_2), 2.42 (s, 3H, CH_3); ^{13}C NMR δ 144.8, 132.9 (s, Ar*C*), 129.8, 127.7 (d, Ar*C*), 72.4, 70.4, 70.2, 70.1, 69.4, 68.4, 61.3 (t, CH_2O), 21.4 (q, CH_3).

***N*-(11-Hydroxy-3,6,9-trioxaundecyl)phthalimide (10).** A suspension of tetraethylene glycol monotosylate **9** (27 g, 77.5 mmol) and potassium phthalimide (14.8 g, 80 mmol) in dry DMF (250 ml) was heated at 100 °C for 8 h. The clear solution was evaporated to dryness and the residue was taken up in EtOAc (500 ml). The organic layer was washed with 1 M HCl solution (2 × 100 ml), brine (1 × 100 ml) and dried over Na_2SO_4. The crude product was purified by column chromatography (silica gel, gradient elution, EtOAc–petroleum ether 7 : 3 to neat EtOAc) to obtain a yellow, clear oil. Yield: 21.2 g (84%). ^{1}H NMR δ 7.9–7.7 (m, 4H, PhthH), 4.2–3.5 (m, 16H, CH_2O, CH_2N); MS (EI) *m*/*z* 324.1 (M + H^+, 324.1).

***N*-[11-(Methylbenzene-4-sulfonyloxy)-3,6,9,-trioxaundecyl]-phthalimide (11).** To a solution of phthalimide **10** (20.7 g, 64 mmol), triethylamine (10 ml, 67 mmol) and DMAP (0.5 g) in CH_2Cl_2 (350 ml) was added portionwise tosyl chloride (12.8 g, 67 mol). The solution was stirred for 6 h at room temperature (check by TLC) and then washed with 1 M HCl solution (1 × 100 ml), brine (1 × 50 ml) and dried over Na_2SO_4. The crude product was purified by column chromatography (silica gel, EtOAc–petroleum ether 1 : 1) to obtain a yellow, clear oil. Yield: 19.6 g (64%). ^{1}H NMR δ 7.9–7.7 (m, 6H, TsH, PhthH), 7.35–7.3 (m, 2H, TsH), 4.2–3.5 (m, 16H, CH_2O, CH_2N), 2.44 (s, 3H, CH_3); MS (EI) *m*/*z* 477.1 (M^+, 477.2).

***N*-[11-(2-Allyloxy-3-formylphenoxy)-3,6,9-trioxaundecyl]-phthalimide (14).** A suspension of 2-allyloxy-3-hydroxybenzaldehyde **13** (6.6 g, 37 mmol), monotosylate **11** (17.7 g, 37 mmol) and anhydrous K_2CO_3 (8.3 g, 60 mmol) in dry acetonitrile (250 ml) was refluxed for 48 h. The mixture was evaporated to dryness and the residue was taken up in EtOAc (250 ml). The organic layer was washed with 1 M HCl (1 × 100 ml), brine (1 × 50 ml) and dried over Na_2SO_4. The crude product was purified by column chromatography (silica gel, gradient elution, EtOAc–petroleum ether 1 : 1 to 7 : 3) to obtain a yellow, clear oil. Yield: 14.9 g (83%). ^{1}H NMR δ 10.43 (s, 1H, CHO), 7.9–7.7 (m, 4H, PhthH), 7.41 (dd, J_1 = 7.6 Hz, J_2 = 1.9 Hz, ArH), 7.17–7.08 (m, 2H, ArH), 6.2–6.0 (m, 1H, =CH), 5.4–5.2 (m, 2H, $=CH_2$), 4.7–4.65 (m, 2H, $ArOCH_2$), 4.2–4.15, 3.9–3.6 (m, 16H, CH_2O, CH_2N); MS (EI) *m*/*z* 483.2 (M^+, 483.2).

***N*-[11-(2-Allyloxy-3-(4,5-dihydro-1,3-dioxol-2-yl)phenoxy)-3,6,9-trioxaundecyl]phthalimide (15).** A solution of phthalimide **14** (14.5 g, 30 mmol), ethylene glycol (1.96 g, 31.5 mmol),

trimethyl orthoformate (6.4 g, 60 mmol) and a catalytic amount of toluene-*p*-sulfonic acid in dry toluene (150 ml) was refluxed for 8 h (check by TLC). After cooling the solution to room temperature, it was washed with saturated $NaHCO_3$ solution (1 × 50 ml), brine (1 × 50 ml) and dried over Na_2SO_4. After evaporation of the solvent, a yellow oil was obtained. Yield: 15.88 g (quantitative). ^{1}H NMR δ 7.9–7.7 (m, 4H, PhthH), 7.2–6.9 (m, 3H, ArH), 5.65 (s, 1H, CHOO), 6.2–6.0 (m, 1H, =CH), 5.4–5.2 (m, 2H, =CH_2), 4.7–4.65 (m, 2H, ArOCH_2), 4.15–3.55 (m, 16H, CH_2O, CH_2N), 3.36 (s, 4H, OCH_2CH_2O); MS (EI) *m*/*z* 527.2 (M^+, 527.3).

11-[2-Allyloxy-3-(4,5-dihydro-1,3-dioxol-2-yl)phenoxy]-3,6,9-trioxaundecylamine (16). A solution of phthalimide **15** (15.7 g, 29.8 mmol) and N_2H_4·H_2O (9 ml, 180 mmol) in MeOH (250 ml) was refluxed for 5 h. After the reaction mixture was cooled to room temperature, it was kept overnight in the freezer (−30 °C). The precipitated phthalhydrazide was filtered off and the mixture was evaporated to dryness. The residue was stirred in CH_2Cl_2 (250 ml). A second portion of precipitated phthalhydrazide was filtered off and the clear solution was washed with brine (1 × 25 ml) and dried over Na_2SO_4. After evaporation of the solvent, a yellow oil was obtained. Yield: 9.3 g (79%). ^{1}H NMR δ 7.15–6.9 (m, 3H, ArH), 6.2–6.0 (m, 1H, =CH), 5.65 (s, 1H, CHOO), 5.4–5.2 (m, 2H, =CH_2), 4.7–4.65 (m, 2H, ArOCH_2), 4.57–4.54, 4.17–4.13, 4.0–3.85 (m, 3 × 2H, CH_2O), 3.77–3.1 (m, 8H, CH_2O), 3.44 (t, 2H, CH_2O), 3.30 (s, 4H, OCH_2CH_2O), 2.9–2.8 (br t, 2H, C$H_2$$NH_2$), 1.6–1.4 (br s, 2H, NH_2); ^{13}C NMR δ 151.8, 146.5 (Ar C-2, C-3), 134.6 (=CH), 132.3 (Ar C1), 123.7 (Ar*C*H), 119.4, 117.3, 114.4 (Ar*C*H, =CH_2), 99.8 (s, CHOO), 74.2, 73.5, 70.9, 70.7, 70.3, 69.8, 68.4 (t, CH_2O), 53.8 (s, OCH_2CH_2O), 41.8 (t, CH_2NH_2); MS (EI) *m*/*z* 399.2 (M^+, 397.2).

Dimethyl 2,3-bis(hydroxycarbonylmethoxy)terephthalate (17). A solution of *tert*-butyl ester **8d** (14.54 g, 32 mmol) in neat CF_3COOH (50 ml) was stirred at room temperature for 3 h. The mixture was evaporated to dryness and the solid residue was dried *in vacuo*. Yield: 10.9 g (quantitative). An analytical sample was obtained by recrystallisation from EtOAc; mp 169–170 °C (EtOAc); ^{1}H NMR (DMSO-d_6) δ 7.50 (s, 2H, ArH), 4.60 (s, 4H, OCH_2), 3.89 (s, 6H, OMe), 3.7–3.0 (br, COOH, H_2O); ^{13}C NMR (DMSO-d_6) δ 169.8 (s, CH_2*C*=O), 165.4 (s, C=O), 150.6 (s, Ar*C*O), 130.1 (s, Ar*C*), 125.6 (d, Ar*C*), 70.3 (t, OCH_2), 52.7 (q, OMe); MS (EI) *m*/*z* 342.1 (M^+, 342.1); elemental analysis, calcd C, 49.13; H, 4.12 found C, 49.13; H, 3.91%.

General procedure B for the conversion of dimethyl 2,3-bis(hydroxycarbonylmethoxy)terephthalate (17) to bisamides

A solution of diacid **17** (1 mol equiv.) in neat $SOCl_2$ (5 ml g^{-1} substrate) was refluxed for 1 h. The solution was evaporated to dryness and the solid residue was dried *in vacuo*. To an ice-cooled solution of the appropriate amine (2 mol equiv.), triethylamine (3 mol equiv.) and a spatula point of DMAP in dry CH_2Cl_2 (100 ml g^{-1} substrate) was added dropwise a solution of the freshly prepared diacid chloride in dry CH_2Cl_2 (100 ml). After addition, the mixture was stirred for 18 h, while it was allowed to warm up to room temperature. The solution was washed with water (2 × 50 ml), brine (1 × 50 ml) and dried over Na_2SO_4. The crude product was purified by column chromatography or recrystallisation.

1,4-Dimethyl 2,3-bis-{*N*-[2-allyloxy-3-(4,5-dihydro-1,3-dioxol-2-yl)phenoxy]-3,6,9-trioxaundecylcarbamoylmethoxy} terephthalate (18). Compound **18** was prepared according to procedure B from diacid **17** (3.87 g, 11.3 mmol), amine **16** (9.0 g, 22.6 mmol), triethylamine (3.5 g, 4.8 ml, 34 mmol). The crude product was purified by column chromatography (silica gel, EtOAc–MeOH 9:1) to obtain a yellow, clear oil. Yield: 9.16 g (74%); ^{1}H NMR δ 7.75–7.6 (s + br t, 4H, ArH, CONH), 7.13, 6.89 (dd, J_1 = 7.9 Hz, J_2 = 1.7 Hz, 2H, ArH), 7.03 (t, J_1 = 8.0 Hz, 2H, ArH), 6.2–6.0 (m, 2H, =CH), 5.64 (s, 1H, CHOO), 5.4–5.2 (m, 2H, =CH_2), 4.55–4.5 (s + m, 8H, ArOCH_2CH=), 4.13, 3.83 (t, J_1 = 4.6 Hz, 4H, OCH_2), 3.92 (s, 6H, OCH_3), 3.75–3.5 (m, 24H, CH_2O, CH_2NH), 3.36 (s, 4H, OCH_2CH_2O); ^{13}C NMR δ 167.9 (s, CH_2*C*=O), 164.6 (s, C=O), 151.7 (s, 2 × Ar*C*O), 146.4 (Ar*C*O), 134.5 (d, =CH), 132.3 (Ar C1), 123.7, 119.3, 117.3, 114.3 (Ar C4, -C5, -C6; =*C*H_2), 128.5 (s, Ar*C*C=O), 126.7 (d, Ar*C*H), 99.8 (s, CHOO), 74.2, 73.0, 70.8, 70.6, 70.4, 69.8, 69.7, 68.3 (t, CH_2O, O*C*H_2C=O), 53.8 (t, OCH_2CH_2O), 52.8 (q, OMe), 39.0 (t, CH_2NH).

Dimethyl 2,3-bis(butylcarbamoylmethoxy)terephthalate (24). Compound **24** was prepared according to procedure B from diacid **17** (2.0 g, 5.8 mmol), *n*-butylamine (950 mg, 13.0 mmol), triethylamine (1.77 g, 2.4 ml, 17.5 mmol). The crude product was purified by column chromatography (silica gel, EtOAc–petroleum ether 4:1) to obtain a clear oil which solidified rapidly upon standing. Yield: 2.19 g (84%). An analytical sample was obtained by recrystallisation from petroleum ether; mp 93–94 °C (petroleum ether); ^{1}H NMR δ 7.7 (s, 2H, ArH), 7.6–7.5 (br t, 2H, CONH), 4.51 (s, 4H, OCH_2), 3.93 (s, 6H, OCH_3), 3.37 (q, J = 7.1 Hz, 4H, NHCH_2), 1.65–1.35 (m, 8H, CH_2), 0.97 (t, J = 7.3 Hz, 6H, CH_3); ^{13}C NMR δ 167.6 (s, CH_2*C*=O), 164.7 (s, C=O), 152.1 (s, Ar*C*O), 128.3 (s, Ar*C*), 126.6 (d, Ar*C*), 73.2 (t, OCH_2), 52.7 (q, OMe), 39.0 (t, $NHCH_2$), 31.5, 20.1 (t, CH_2), 13.8 (q, CH_3); MS (EI) *m*/*z* 452.2 (M^+, 452.3); elemental analysis calcd C, 58.40; H, 7.13; N, 6.19; found C, 58.35; H, 7.12; N, 6.22%.

General procedure C for the reduction of dimethyl 2,3-bis-substituted-terephthalates with $LiAlH_4$

A suspension of $LiAlH_4$ (3 mol equiv.) in dry THF (25 ml g^{-1} substrate) was refluxed for 0.5 h and then cooled in an ice-bath. A solution of the appropriate dimethyl terephthalate (1 mol equiv.) in dry THF (10 ml g^{-1} substrate) was added dropwise to the pre-treated suspension of $LiAlH_4$. After addition, the reaction mixture was stirred for 2 h at 0 °C. The ice bath was removed and the solution was stirred for another 2 h, while slowly warming up to room temperature. The excess of $LiAlH_4$ was quenched with 1 M HCl solution until a final acidity of pH = 1 was reached (**CAUTION**, H_2 evolution). When all aluminium salts had dissolved, the THF layer was separated and the water layer was extracted with EtOAc (2 × 150 ml). The combined organic layers were washed with brine (1 × 100 ml) and dried over Na_2SO_4.

1,4-Bis(hydroxymethyl)-2,3-dihydroxybenzene. [Scheme 4] was prepared according to procedure C from $LiAlH_4$ (0.25 g, 6.6 mmol) and dimethyl terephthalate **6** (0.5 g, 2.2 mmol). Yield: 0.3 g (80%); ^{1}H NMR δ 7.3, 6.75 (d, 1H, ArH), 6.2 (s, 2H, OH), 4.7 (s, 2H, CH_2), 3.85 (m, 4H, CH_2, OH); ^{13}C NMR δ 144.4 (s, Ar*C*OH), 128.1 (s, Ar*C*CH_2), 119.8 (d, Ar*C*H), 61.8 (t, CH_2OH); FTIR ν (cm^{-1}) 3323 (O–H), 1462 (CH_2–OH), 1250 (C–O, phenolic), 982, 937 (C–O, primary alcohol).

2,3-Bis[*N*-(2-allyloxy-3-formylphenoxyl)-3,6,9-trioxaundecyl-carbamoyl methoxy]-1,4-bis(hydroxymethyl)benzene (19). 19 was prepared according to procedure C from $LiAlH_4$ (0.95 g, 25 mmol) and dimethyl terephthalate **18** (9.1 g, 8.26 mmol). After work-up and evaporation, a sticky oil was obtained in almost quantitative yield, which was not purified further. Yield: 7.88 g; ^{1}H NMR δ 10.4 (s, 2H, CHO), 8.0–7.9 (br t, 2H, CONH), 7.5–7 (m, 8 H, ArH), 6.2–6.0 (m, 2H, =CH), 5.4–5.2 (m, 2H, =CH_2), 4.62 (d, 4H, CH_2OH), 4.43 (s, 4H, OCH_2CO), 4.7–4.65, 4.2–3.4 (m, 36H, ArOCH_2CH=, CH_2O, CH_2NH); ^{13}C NMR δ 190.4 (s, CHO), 169.0 (s, CH_2*C*=O), 152.2, 151.6, 149.2 (s, Ar*C*O [C2, C3, C7]), 134.5 (d, =CH), 133.4 (s, Ar*C(8)*CH_2), 130.1 (s, Ar C1), 125.1 (d, Ar*C(9)*H), 124.1, 119.9, 119.6, (d, Ar C4, -C5,

-C6), 118.9 (t, =CH_2), 75.1 (t, OCH_2C=), 72.1, 70.7 (2×), 70.6, 70.2, 69.8, 69.6, 68.7 (t, CH_2O, OCH_2C=O), 60.6 (t, CH_2OH), 38.9 (t, CH_2NH); MS (FAB) *m*/*z* 957 ($M + H^+$, 957.5).

1,4-Bis(hydroxymethyl)-2,3-bis(butylcarbamoylmethoxy)-benzene (25). 25 was prepared according to procedure C from $LiAlH_4$ (0.5 g, 13.3 mmol) and dimethyl terephthalate **24** (2.0 g, 4.42 mmol). After work-up and evaporation a white solid was obtained, which was further purified by recrystallisation from EtOAc–MeOH. Yield: 1.25 g (71%); mp 157–158 °C (EtOAc–MeOH); ^{1}H NMR ($CDCl_3$–DMSO-d_6) δ 7.7–7.5 (br t, 2H CONH) 7.7 (s, 2H, ArH), 4.61 (d, 4H, CH_2OH), 4.95 (t, 2H, OH), 4.45 (s, 4H, OCH_2CO), 3.37 (q, J = 7.1 Hz, 4H, NHCH_2), 1.65–1.35 (m, 8H, CH_2), 0.97 (t, J = 7.3 Hz, 6H, CH_3); ^{13}C NMR ($CDCl_3$–DMSO-d_6) δ 168.5 (s, CH_2C=O), 148.9 (s, Ar*C*O), 135.1 (s, Ar*C*), 125.0 (d, Ar*C*), 72.2 (t, OCH_2), 60.0 (t, *C*H_2OH), 38.7 (t, $NHCH_2$), 31.4, 20.0 (t, CH_2), 13.7 (q, CH_3); MS (EI) *m*/*z* 397.2 ($M + H^+$, 397.3); elemental analysis, calcd C, 60.59; H, 8.13; N, 7.06; found C, 60.45; H, 8.08; N, 6.96%.

1,4-Bis(hydroxymethyl)-2,3-bis(benzyloxy)benzene (27). 27 was prepared according to procedure C from $LiAlH_4$ (0.57 g, 15.0 mmol) and dimethyl terephthalate **8b** (2.0 g, 4.92 mmol). After work-up and evaporation almost pure **27** in quantitative yield was obtained as a white solid. Yield: 1.71 g. An analytical sample was obtained by recrystallisation from petroleum ether (70%); mp 104–105 °C (EtOAc–petroleum ether); ^{1}H NMR δ 7.4–7.3 (m, 10H, BnH), 7.06 (s, 2H, ArH), 5.2 (s, 4H, OCH_2C), 4.57 (s, 4H, CH_2O), 2.4–2.1 (br s, 2H, OH); ^{13}C NMR δ 149.6 (s, ArC), 137.1 (s, Bn*C*), 135.4 (s, ArC), 128.7, 128.6, 128.5 (d, Bn*C*H), 124.2 (d, Ar*C*), 75.5 (t, OCH_2), 61.3 (t, *C*H_2OH); elemental analysis, calcd C, 75.41; H, 6.33; found C, 75.50; H, 6.22%.

Bis-2,3-(*N*-[11-(2-hydroxy-3-formylphenoxy)-3,6,9-trioxa-undecyl]carbamoylmethoxy)-1,4-bis(hydroxymethyl)benzene (20). To a solution of compound **19** (3.0 g, 3.13 mmol), in ethanol–water (4:1) (60 ml) was added 38 ml of a solution of freshly prepared solution of triethylammonium formate (1 M, ethanol–water 4:1, pH = 8). A spatula-point of $Pd(CH_3COO)_2$ and a few flakes of triphenylphosphine were added. The mixture was refluxed for 1.5 h and regularly checked by TLC (EtOAc–MeOH 4:1). The mixture was evaporated to dryness. The residue was taken up in EtOAc (500 ml) and washed with a minimum of water, brine and dried over Na_2SO_4. The crude product was purified by column chromatography (silica gel, EtOAc–MeOH 4:1). A light yellow oil was obtained, which was almost pure. Yield: 1.70 g (62%); ^{1}H NMR δ 10.0 (s, 2H, CHO), 8.0–7.9 (br t, 2H, CONH), 7.23, 7.14 (dd, J_1 = 7.9 Hz, J_2 = 1.7 Hz, 2H, ArH), 6.91 (t, J_1 = 8.0 Hz, 2H, ArH), 7.03 (s, 2H, ArH), 4.66 (d, 4H, CH_2OH), 4.51 (s, 4H, OCH_2CO), 4.2–3.5 (m, 32H, CH_2O, CH_2NH); ^{13}C NMR δ 195.8 (s, CHO), 169.0 (s, CH_2C=O), 152.1 (s, Ar*C(2)*O), 147.4 (s, Ar*C(3)*O), 149.3 (s, Ar*C(7)*O), 134.4 (s, Ar*C(8)*CH_2), 125.2 (d, Ar*C(9)*H), 121.5 (s, Ar C1), 124.9, 120.7, 119.6, (d, Ar C4, -C5, -C6), 72.1, 70.7, 70.5, 70.2, 69.9, 69.6, 69.2 (t, CH_2O, OCH_2C=O), 60.8 (t, CH_2OH), 38.9 (t, CH_2NH); MS (FAB) *m*/*z* 877 ($M + H^+$, 877.4), 899 ($M + Na^+$, 899.4).

***trans*-3,5,20,28-Tetraaza-8,11,14,17,23,25,31,34,37,40-decaoxa-1,7(1,3),24(1,2)-benzena-4(1,2)cyclohexana-24^3,24^6-bis(hydroxymethyl)-1^2,7^2-dihydroxytetracontacyclophane-2,5-diene-21,27-dione (21).** A solution of compound **20** (1.70 g, 1.94 mmol) and $Ba(OTf)_2$ (1.7 g, 3.9 mmol) in dry THF (2 L) was refluxed for 1 h. (±)-*trans*-Cyclohexane-1,2-diamine (222 mg, 1.94 mmol) was added and refluxing was continued for another 1.5 h. The mixture was evaporated to dryness and the residue was taken up in CH_2Cl_2. The solution was washed with water (1 × 250 ml), dilute Na_2SO_4 solution (1 × 100 ml) and dried over Na_2SO_4. The crude product was separated by column chromatography (silica gel, CH_2Cl_2–MeOH 9:1; 1 vol% $EtMe_2N$) to obtain macrocyclic salen **21** as a deep yellow amorphous solid. Yield: 902 mg (50%); ^{1}H NMR δ 14–13.5 (br, 2H, OH), 8.22 (s, 2H, CH=N), 8.2–8.0 (br m, 2H, CONH), 7–6.5 (m, 8H, ArH), 4.60–4.3 (m, 8H, CH_2OH, OCH_2CO), 4.2–3.2 (m, 32H, CH_2O, CH_2NH), 2.2–1.3 (br m, 8H, CH_2 [cyclohexyl]); ^{13}C NMR δ 169.1 (s, CH_2C=O), 164.8 (d, CH=N), 151.9, 148.9, 147.2 (s, Ar C2, C3, C7), 133.6 (s, Ar*C(8)*CH_2), 124.5 (d, Ar*C(9)*H), 123.7, 118.0, 116.5 (d, Ar C4, C5, C6), 118.8 (s, Ar C1), 77.0 (d, C[cyclohexyl]HN), 72.8, 72.0, 70.7, 70.6, 70.4, 70.0, 69.8, 68.6 (t, CH_2O, OCH_2C=O), 60.9 (t, CH_2OH), 39.0 (t, CH_2NH), 33.3, 24.3 (t, CH_2 [cyclohexyl]); MS (FAB) *m*/*z* 954.0 (M^+, 954).

Metallation of macrocyclic salen 21. To a slightly warmed (± 40 °C) solution of macrocyclic salen **21** (600 mg, 0.63 mmol) in MeOH (20 ml) was added a methanolic $Ni(OAc)_2 \cdot 4H_2O$ solution (9.4 ml, 0.1 M). The deep red solution was gently warmed for 1 min (the temperature must not exceed 50 °C) and evaporated to dryness. The residue was taken-up in CH_2Cl_2 and washed with water (3 × 100 ml) [it is crucial that distilled water be used at this stage]. The organic layer was filtered over Hiflo to clear it from residual dispersed water. After evaporation pure metallated **22** was obtained as a deep red solid in almost quantitative yield. Yield: 637 mg; ^{1}H NMR ($CDCl_3$) δ 8.5–8.4 (br t, 2H, CH=N), 7.37 (s, 2H, CONH), 7.0 (s, 2H, ArH*(9)*), 6.82, 6.75 (d, J = 7.7 Hz, 2H, ArH), 6.47 (t, J = 7.7 Hz, 2H, ArH), 4.61 (s, 4H, CH_2OH), 4.55 (s, 4H, OCH_2CO), 4.2–4.1 (m, 4H, CH_2O), 3.8–3.5 (m, 28H, CH_2O, CH_2NH), 3.2–3.1, 2.5–2.3, 2.0–1.8 (br m, 2H, CH, CH_2 [cyclohexyl]), 1.4–1.2 (br m, 4H, CH, CH_2 [cyclohexyl]), 2.7–2.6 (br, 2H, OH); ^{13}C NMR (CD_2Cl_2) δ 169.6 (s, CH_2C=O), 158.1 (d, C=N), 157.0 (s, Ar*C(2)*O), 150.2, 149.9 (s, Ar*C(3)*O), Ar*C(7)*O), 135.9 (s, Ar*C(8)*CH_2), 125.7 (d, Ar*C(9)*H), 121.7 (s, Ar C1), 126.7, 118.7, 114.4 (d, Ar C4, C5, C6), 77.0 (s, CHN=), 73.0, 71.3, 70.9, 70.5, 70.3, 69.1 (t, CH_2O, OCH_2C=O), 61.2 (t, CH_2OH), 39.7 (t, CH_2NH), 29.3, 25.2 (t, CH_2 [cyclohexyl]); MS (FAB, glycerol) *m*/*z* 1034 ($M + Na^+$, 1033.5), 1050 ($M + K^+$, 1049.5).

General procedures for the conversion of 1,4-bis(hydroxymethyl)-2,3-bis(substituted)-benzenes to 1,4-bis(chloromethyl)-2,3-bis(substituted)-benzenes

Procedure D. A solution of the appropriate bis(hydroxymethylated) derivative (1 mol equiv.) and $SOCl_2$ (5–10 mol equiv.) in dry CH_2Cl_2 (25 ml g^{-1} substrate) was refluxed for 1 h. The solution was diluted with additional CH_2Cl_2 and washed with $NaHCO_3$ solution (stad. 50 ml portions) until the water layer was basic. The organic layer was dried over Na_2SO_4. The crude products after work-up had enough purity to be used without any further purification. Analytical samples could be obtained by recrystallisation.

Procedure E. This is similar to procedure D, however, $SOCl_2$ (3 mol equiv.) and additional 2,6-lutidine (3.3 mol equiv.) were used. The reaction was performed at room temperature (reaction time 1 h). The organic layer was washed with NH_4Cl solution (satd., 1 × 50 ml).

Procedure F. A solution of the appropriate bis(hydroxymethylated) derivative (1 mol equiv.), mesyl chloride (3–4 mol equiv.) and triethylamine (3–4 mol equiv.) in dry, ethanol free $CHCl_3$ (50 ml g^{-1} substrate) was heated at 55 °C for 2 h. $Et_3N \cdot HCl$ (10 mol equiv.) was added in one portion to the mixture and heating was continued for another 4 h. After cooling the mixture was diluted with additional CH_2Cl_2. The solution was washed with water, brine and dried over Na_2SO_4. The crude products were purified by recrystallisation.

1,4-Bis(chloromethyl)-2,3-dihydroxybenzene (7). 7 was prepared according to procedure E, using 1,4-bis(hydroxymethyl)-2,3-dihydroxybenzene (0.08 g, 0.5 mmol). Yield: 0.075 g (90%); ^{1}H NMR δ 7.3, 6.85 (d, 1H, ArH), 4.65–3.9 (br, 4H, CH_2Cl);

^{13}C NMR δ 142.9 (s, Ar*C*OH), 128.5 (s, Ar*C*CH_2), 120.1 (d, Ar*C*H), 40.2 (t, CH_2Cl); FTIR ν (cm^{-1}) 3470 (O–H), 1441 (CH_2–Cl), 1263 (C–O, phenolic), 691 (C–Cl).

Ni-salen complex of *trans*-3,5,20,28-tetraaza-8,11,14,17,23,25,31,34,37,40-decaoxa-1,7(1,3),24(1,2)-benzena-4(1,2)cyclohexana-24^3,24^6-bis(chloromethyl)-1^2,7^2-dihydroxy-tetraconta-cyclophane-2,5-diene-21,27-dione (23). 23 was prepared according to procedure F using macrocyclic salen **22** (400 mg, 0.395 mmol), mesyl chloride (181 mg, 1.58 mmol), triethylamine (160 mg, 1.58 mmol) and $Et_3N{\cdot}HCl$ (544 mg, 3.95 mmol). After reaction, the mixture was washed with water (4 × 100 ml) [it is crucial that distilled water be used at this stage] and filtered over Hiflo to clear it from residual dispersed water. After evaporation the crude chloromethylated macrocycle **23** was not further purified, but stored in a freezer. Crude yield: 442 mg; ^{1}H NMR (CD_2Cl_2) δ 7.5–6.3 (br m, 12H, CH=N, CONH, ArH*(9)*, ArH), 4.7–4.4 (m, 8H, C*H*$_2$Cl, OCH_2CO), 4.2–3.3 (m, 28H, CH_2O, CH_2NH), 3.2–3.1, 2.5–2.3, 2.0–1.8 (br m, 2H, CH, CH_2 [cyclohexyl]), 1.4–1.2 (br m, 4H, CH, CH_2 [cyclohexyl]); ^{13}C NMR (CD_2Cl_2) δ 168.8 (s, CH_2C=O), 158.9 (d, C=N), 155.3 (s, Ar*C(2)*O), 150.2, 149.8 (s, Ar*C(3)*O), Ar*C(7)*O), 133.8 (s, Ar*C(8)*CH_2), 126.2 (d, Ar*C(9)*H), 121.3 (s, Ar C1), 127.2, 117.3, 115.6 (d, Ar C4, C5, C6), 73.0–68.0 (t, CH_2O, O*C*H_2C=O), 41.7 (t, CH_2Cl), 39.6 (t, CH_2NH), 29.4, 25.1 (t, CH_2 [cyclohexyl]); MS (ES) *m/z* 1047.5, 1049.5 ($M + H^+$, 1047.3, 1049.3), 1069.3, 1071.3 ($M + Na^+$, 1069.3, 1071.3).

1,4-Bis(chloromethyl)-2,3-bis(butylcarbamoylmethoxy)benzene (26). 26 was prepared according to procedures D–F. In a typical preparation, applying procedure E, compound **25** (500 mg, 1.26 mmol), $SOCl_2$ (452 mg, 3.8 mmol) and 2,6-lutidine (450 mg, 4.2 mmol) were used. After work-up almost pure **26** was obtained as a white solid in quantitative yield. An analytical sample was prepared by recrystallisation from EtOAc–petroleum ether. Yield: 545 mg; mp 129–130 °C (EtOAc–petroleun ether); ^{1}H NMR ($CDCl_3$) δ 7.17 (s, 2H, ArH), 6.8–6.7 (br t, 2H, CONH) 4.56, 4.51 (s, 4H, CH_2Cl, OCH_2CO), 3.37 (q, J = 7.1 Hz, 4H, NHC*H*$_2$), 1.65–1.35 (m, 8H, CH_2), 0.97 (t, J = 7.3 Hz, 6H, CH_3); ^{13}C NMR ($CDCl_3$) δ 167.8 (s, CH_2C=O), 149.2 (s, Ar*C*O), 133.0 (s, Ar*C*), 127.0 (d, Ar*C*), 72.3 (t, OCH_2), 40.7 (t, *C*H_2Cl), 39.2 (t, $NHCH_2$), 31.5, 20.1 (t, CH_2), 13.7 (q, CH_3); MS (EI) *m/z* 432.2 (M^+, 432.0); elemental analysis calcd C, 55.40; H, 6.98; N, 6.46; found C, 55.77; H, 6.85; N, 6.49%.

1,4-Bis(chloromethyl)-2,3-bis(benzyloxy)benzene (28). 28 was prepared according to procedure D using compound **27** (500 mg, 1.43 mmol) and $SOCl_2$ (1.7 g, 1 ml, 14 mmol). After work-up almost pure **28** was obtained as a slightly yellow solid in quantitative yield. An analytical sample was prepared by recrystallisation from petroleum ether. Yield: 550 mg; mp 89–90 °C (petroleum ether); ^{1}H NMR δ 7.5–7.3 (m, 10H, BnH); 7.16 (s, 2H, ArH), 5.15 (s, 4H, OCH_2), 4.57 (s, 4H, CH_2Cl); ^{13}C NMR δ 150.3 (s, ArC), 136.8 (s, Bn*C*), 133.2 (s, ArC), 128.6, 128.5, 128.4 (d, Bn*C*H), 125.9 (d, Ar*C*), 75.3 (t, O*C*H_2), 40.8 (t, *C*H_2Cl); MS (EI) *m/z* 386.1 (M^+, 386.2); elemental analysis, calcd C, 68.21; H, 5.20; found C, 68.91; H, 5.15%.

Electrolysis of macrocyclic Ni-salen 23 to the corresponding PPX oligomer. A solution of **23** (400 mg, 0.38 mmol) in DMF–Et_4NBr (0.1 M, 30 ml) was electrolysed at a mercury pool at constant potential of −1.22 V (Ag/AgBr). The electrolysis was followed by recording CV's at regular intervals. When a total charge of 90 C was passed, the red DMF solution was evaporated to dryness. The residue was suspended in distilled water and extracted with CH_2Cl_2 (2 × 100 ml). The organic layer was washed with distilled water (5 × 50 ml), but **not** dried over dehydrated salts. Evaporation gave a red solid, which was dried *in vacuo*. Yield 315 mg (85%); ^{1}H NMR (CD_2Cl_2) δ 8.0–6.3 (br m, 12H, CH=N, CONH, ArH*(9)*, ArH), 4.7–3.3 (m, 36H, OCH_2CO, CH_2O, CH_2NH), 3.2–3.1, 2.5–1.3 (br m, 14H, CH, CH_2 [cyclohexyl], $ArCH_2$, $ArCH_3$); ^{13}C NMR (CD_2Cl_2) δ 169.1 (s, CH_2C=O), 158.2 (d, C=N), 150.4 (br s, Ar*C(3)*O), Ar*C(7)*O), 132.6, 130.1 (s, Ar*C(8)*CH_2), 127–126 (br d, Ar*C(9)*H), 121.6 (s, Ar C1), 127.5, 118.1, 114.4 (d, Ar C4, C5, C6), 73.0–69.0 (t, CH_2O, O*C*H_2C=O), 39.6 (t, CH_2NH), 30.4 (t, Ar*C*H_2–*C*H_2Ar), 29.3, 25.2 (t, CH_2 [cyclohexyl]), 16.6 (q, $ArCH_3$).

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