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The synthesis of aromatic diazatricycles from phenylenediamine-bis(methylene Meldrum's acid) derivatives

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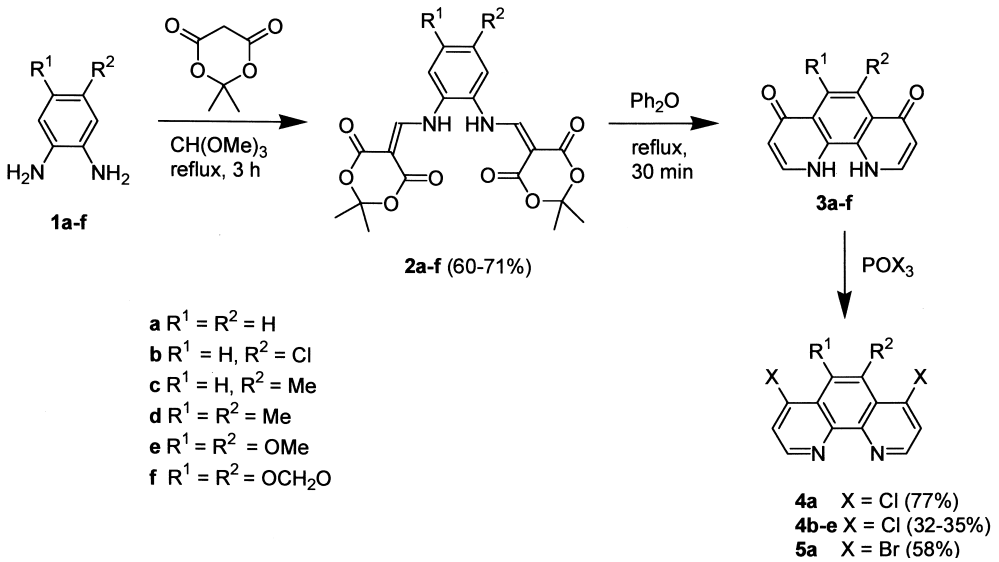
Abstract—The thermocyclisation of phenylenediamine-bis(methylene Meldrum's acid) derivatives has been investigated. Those of *o*-phenylenediamines give 1,10-phenanthroline derivatives, while those of *m*- and *p*-phenylenediamines lead to the preferential formation of angular diazatricycles. Thus, for example, the di-Meldrum's acid derivative of 2,5-dichloro-1,4-phenylenediamine gives, via *ipso*-substitution, the unexpected angular product **19**.

1. Introduction

Diazatricycles, whose properties are especially exemplified by the 1,10-phenanthroline nucleus, have found applications as chelating agents,[1] catalyst ligands,[2] cytotoxic drugs,[3a–e] model structures for NMR studies,[4] base components of solvatochromic compounds,[5] and building blocks in supramolecular chemistry.[6] From a synthetic point of view, those obtained from phenylenediamines are of particular interest since both outer rings can be constructed simultaneously. 1,1,3-Triethoxypropane,[7] crotonaldehyde,[7] ethyl ethoxalylacetate,[7] dimethyl acetylenedicarboxylate,[3a] diethyl ethoxymethylenemalonate[3a,8] and ethyl α,α-formylphenylacetate,[9] for example, have all been successfully used in such transformations. On the other hand, a double cyclisation strategy with analogs of 5-arylaminemethylene Meldrum's



Scheme 1.

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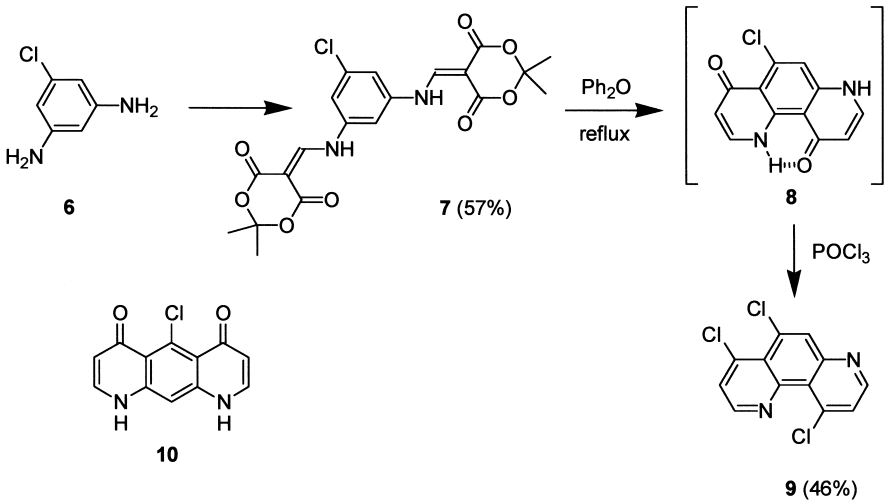
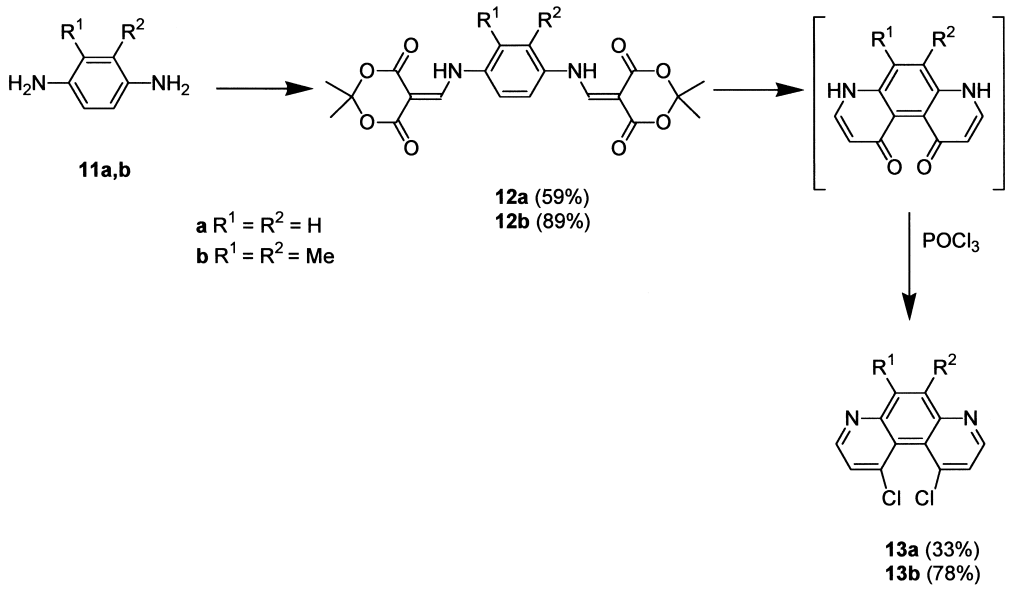


Scheme 2.

acid[10] has so far not been described. We report now the synthesis of diazatricycles based on the thermal decarboxylation/cyclisation of phenylenediamine-bis(methylene Meldrum's acid) derivatives. Substituent stability/effects and regioselectivity of the ring closures have been investigated for all three phenylenediamine isomers.

2. Results and discussion

In order to avoid the formation of possible regioisomers and to probe the proposed methodology, we decided to begin our studies with *o*-phenylenediamines. Thus, reaction of *o*-phenylenediamines **1a**–**f** with 2 equiv. of 5-methoxymethylene Meldrum's acid (generated in situ) in trimethyl orthoformate at reflux gave the novel bis-adducts **2a**–**f** in moderate yields (Scheme 1). In contrast to **2a**,**d**–**f**, compounds **2b**,**c** do not display all expected carbon signals in their ^{13}C NMR spectra (16 and 15 instead of 18 and 19, respectively). This may be a consequence of the Meldrum's acid groups being to remote from the unsymmetrically substituted benzene rings in order for the asymmetry to be felt completely. However, all other spectroscopic data were in full agreement with the proposed structures. The thermal decarboxylation/cyclisation of compounds **2a**–**f** was carried out under high dilution conditions in refluxing diphenyl ether according to the method reported by Cassis et al.[11] Subsequent treatment of the rather insoluble crude phenanthrolones **3a**–**f** with phosphoryl chloride furnished the expected, more soluble and characterisable 4,7-dichloro-1,10-phenanthrolines. However, while the parent compound **4a** was obtained in a better yield (77%) than previously reported,[8] the novel 5- and 5,6-substituted analogs **4b**–**e** were isolated in only 32–35% yield. Steric clash between the carbonyl-oxygen and the 5/6-substituent(s) in the precursors **3b**–**e** may explain the lower yields observed for the latter. In addition, compound **3f** failed to give the corresponding phenanthroline derivative, presumably due to loss of the methylene group of the methylenedioxy substituent and further decomposition of the resulting diol under the reaction conditions. However, treatment of compound **3a** with phosphoryl bromide gave the expected



Scheme 3.

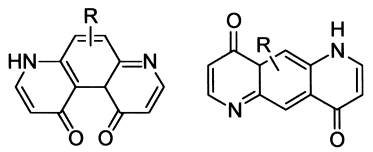


Figure 1.

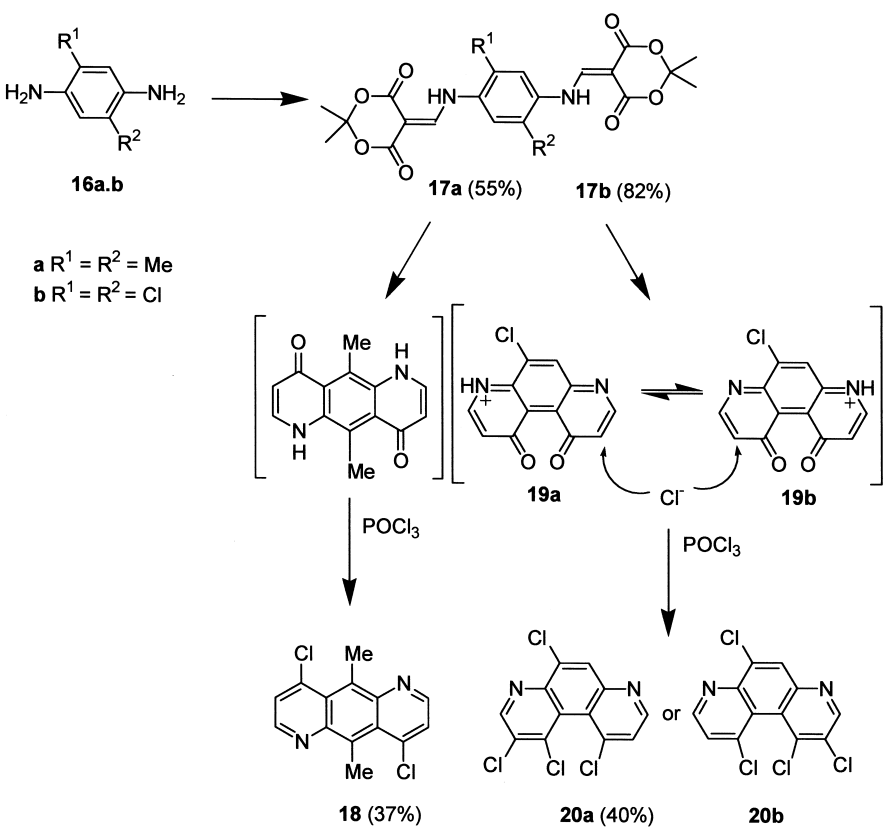
4,7-dibromo-phenanthroline **5**, again, via a shorter route and better yield (58%) than previously described (Scheme 1).[12] Phenanthrolines of the type **4** and **5** have recently been used and are important precursors to macrocyclic oligophenanthroline ligands with *exo*-coordination sites.[13]

Having established the general principle, we then decided to subject 5-chloro-1,3-phenylenediamine (**6**) to the same reaction sequence. Thus, treatment of compound **6** with Meldrum's acid in trimethyl orthoformate followed by cyclisation in diphenyl ether and reaction with phosphoryl chloride resulted in the exclusive formation of 1,7-phenanthroline **9** (Scheme 2). As expected, compound **9** showed twelve resonances in the ^{13}C NMR spectrum. The observed regioselectivity may be a consequence of intramolecular hydrogen bonding which is only possible in intermediate **8** when compared to the alternative C_2-symmetrical cyclisation product **10**. Similarly, *p*-phenylenediamines **11a**,**b** gave compounds **13a**,**b** as the sole products (Scheme 3). Assuming that these transformations proceed via double sequential electrocyclisations of the corresponding ketene derivatives generated upon thermolysis,[14] the exclusive formation of, in particular, 4,7-phenanthroline **13a**[3a] can be attributed to higher conjugation in the angular- versus the linear intermediates **14** and **15**, respectively (Fig. 1).

The same trend was observed with 2,5-disubstituted-*p*-phenylenediamines. Thus, while cyclisation of the di-Meldrum's acid derived from *p*-phenylenediamine **16a** gave the expected ellipticine[15] analogue 4,8-dichloro-5,7-dimethylpyrido[2,3-*g*]quinoline (**18**), cyclisation of the dichloro derivative **17b** resulted in the exclusive formation of the *ipso*-substituted product **20a** (or **b**) via chloride trapping of the cationic intermediate **19a** (or **b**) (Scheme 4). Although the two possible isomers **20a**,**b** could not be distinguished from one another, the preferential formation of the angular versus the linear product was clear from the spectroscopic assignment of the product. Both, the ^{1}H and ^{13}C NMR spectra showed that the compound lacked C_2 symmetry with two distinct doublets, two distinct singlets and 12 resonances in the aromatic region, respectively. In addition, all other spectroscopic data were consistent with the proposed structures.

3. Conclusion

We have developed a short and efficient route for the synthesis of various diazatricycles. The reaction sequence tolerates a wide range of functional groups and is in some cases better than or complementary to existing methods. In addition, the ring-closing reaction turns out to be highly regioselective, giving preferentially angular products.



Scheme 4.

4. Experimental

4.1. General procedures

All reactions were conducted in oven or flame dried glassware. Reaction temperatures reported refer to external bath temperatures. Hexanes refers to the petroleum fraction bp 40–60°C. *o*-Phenylenediamines **1e**,**f** were prepared as reported elsewhere.[16,17] All other reagents were used as commercially supplied. TLC was carried out on E. Merck precoated silica gel 60 F_{254} plates; compounds were visualised using UV radiation (254 nm). Chromatography refers to flash chromatography on E. Merck silica gel 60, 40–60 μm (eluants are given in parentheses).

4.2. General procedure for the synthesis of phenylenediamine-bis(methylene Meldrum's acid) derivatives

A solution of Meldrum's acid (70 mmol) in trimethyl orthoformate (100 mL) was refluxed for 2 h under N_2. To this solution the corresponding phenylenediamine (30 mmol) was added and the resulting mixture heated at reflux for a further hour. Rotary evaporation followed by recrystallisation gave the bis-adducts shown below.

4.2.1. 1,2-Bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (2a). Colourless crystalline solid (70%): mp >209°C (EtOH, decomp.); R_f 0.56 (EtOAc); IR (nujol): 1677, 1728, 3268 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 1.74 (s, 12H), 7.50 (m, 4H), 8.58 (d, *J*=14.4 Hz, 2H), 11.44 (br d, *J*=14.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 27.2, 89.6, 105.5, 121.4, 128.6, 131.2, 155.0, 163.0, 165.4; MS (FAB) 416 ($M^{+\cdot}$). Anal. calcd for $C_{20}H_{20}N_2O_8$: C, 57.69; H, 4.84; N, 6.73. Found: C, 57.84; H, 4.74; N, 6.65.

4.2.2. 4-Chloro-1,2-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (2b). Green plates (62%): mp >200°C (CH_3CN, decomp.); R_f 0.57 (EtOAc); IR (nujol): 1675, 1735, 3070 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 1.76 (s, 12H), 7.42–7.50 (m, 3H), 8.48 (d, *J*=15.6 Hz, 1H), 8.52 (d, *J*=15.6 Hz, 1H), 11.30 (br d, *J*=15.6 Hz, 1H), 11.50 (br d, *J*=15.6 Hz, 1H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 27.1, 89.9, 90.2, 105.57, 105.63, 121.1, 122.8, 128.2, 129.6, 132.3, 134.2, 154.3, 155.0, 162.7, 162.8, 165.3; MS (FAB) 451 ($M^{+\cdot}$). Anal. calcd for $C_{20}H_{19}ClN_2O_8$: C, 53.28; H, 4.25; N, 6.21. Found: C, 53.23; H, 4.13; N, 6.35.

4.2.3. 4-Methyl-1,2-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (2c). Yellow crystalline solid (67%): mp >210°C (CH_3CN, decomp.); R_f 0.61 (EtOAc); IR (nujol): 1670, 1730, 3160 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 1.80 (s, 12H), 2.46 (s, 3H), 7.28–7.40 (m, 3H), 8.56 (d, *J*=14.4 Hz, 1H), 8.60 (d, *J*=14.4 Hz, 1H), 11.28 (br d, *J*=14.4 Hz, 1H), 11.48 (br d, *J*=14.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 21.0, 27.1, 89.2, 89.4, 105.4, 121.2, 121.6, 128.4, 129.0, 131.0, 139.4, 154.5, 155.3, 163.0, 165.4; MS (FAB) 430 ($M^{+\cdot}$). Anal. calcd for $C_{21}H_{22}N_2O_8$: C, 58.60; H, 5.15; N, 6.51. Found: C, 58.61; H, 4.94; N, 6.56.

4.2.4. 4,5-Dimethyl-1,2-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (2d). Orange crystalline solid (71%): mp >210°C (CH_3CN, decomp.); R_f 0.59 (EtOAc); IR (nujol): 1675, 1730, 3170 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 1.78 (s, 12H), 2.34 (s, 12H), 7.20 (s, 2H), 8.50 (d, *J*=13.2 Hz, 2H), 11.33 (br d, *J*=13.2 Hz, 2H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 19.5, 27.2, 89.0, 105.4, 122.3, 128.7, 137.9, 155.1, 163.2, 165.4; MS (FAB) 444 ($M^{+\cdot}$). Anal. calcd for $C_{22}H_{24}N_2O_8$: C, 59.45; H, 5.44; N, 6.30. Found: C, 59.43; H, 5.34; N, 6.31.

4.2.5. 4,5-Dimethoxy-1,2-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (2e). Yellow needles (60%): mp >190°C (CH_3CN, decomp.); R_f 0.40 (EtOAc); IR (nujol): 1680, 1725, 3290 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 1.72 (s, 12H), 3.96 (s, 12H), 6.86 (s, 2H), 8.40 (d, *J*=14.4 Hz, 2H), 11.40 (br d, *J*=14.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 25.1, 54.8, 86.5, 103.0, 103.3, 122.3, 147.3, 153.7, 161.4, 163.5; MS (FAB) 476 ($M^{+\cdot}$). Anal. calcd for $C_{22}H_{24}N_2O_{10}$: C, 55.46; H, 5.08; N, 5.88. Found: C, 55.25; H, 4.96; N, 5.87.

4.2.6. 4,5-Methylenedioxyl-1,2-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)-amino]benzene (2f). Green plates (68%): mp >210°C (CH_3CN, decomp.); R_f 0.61 (EtOAc); IR (nujol): 1683, 1725, 3221 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 1.74 (s, 12H), 6.14 (s, 2H), 6.92 (s, 2H), 8.44 (d, *J*=14.4 Hz, 2H), 11.28 (br d, *J*=14.4 Hz, 2H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 27.2, 89.2, 102.0, 103.0, 105.5, 125.4, 148.0, 155.0, 163.1, 165.5; MS (FAB) 460 ($M^{+\cdot}$). Anal. calcd for $C_{21}H_{20}N_2O_{10}$: C, 54.78; H, 4.38; N, 6.08. Found: C, 54.92; H, 4.26; N, 6.28.

4.2.7. 5-Chloro-1,3-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (7). Colourless solid (57%): mp >221°C (EtOAc, decomp.); IR (KBr): 1682, 1728, 3158, 3228 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.75 (s, 12H), 7.15 (s, 1H), 7.17 (s, 2H), 8.64 (d, *J*=13.7 Hz, 2H), 11.24 (br d, *J*=13.7 Hz, 2H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 27.1, 89.1, 105.6, 105.8, 115.6, 137.7, 140.5, 152.1, 162.9, 165.2; MS (EI) 450 ($M^{+\cdot}$); HRMS (FAB) calcd for $C_{20}H_{19}ClN_2O_8$: ($M^{+\cdot}$) 450.0830, found ($M^{+\cdot}$) 450.0844. Anal. calcd for $C_{20}H_{19}ClN_2O_8$: C, 53.28; H, 4.25; N, 6.21. Found: C, 53.40; H, 4.50; N, 6.54.

4.2.8. 1,4-Bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (12a). Orange crystalline solid (59%): mp >272°C (DMF, decomp.); IR (KBr): 1672, 1732, 3158 cm^{-1}; ^1H NMR (CF_3COOD, 200 MHz) δ 1.71 (s, 12H), 7.46 (s, 4H), 8.79 (d, *J*=13.8 Hz, 2H), 11.35 (d, *J*=13.8 Hz, 2H); ^{13}C NMR (CF_3COOD, 50 MHz) δ 26.1, 86.8, 109.5, 121.5, 137.9, 155.5, 169.4, 169.5; MS (EI) 416 ($M^{+\cdot}$). Anal. calcd for $C_{20}H_{20}N_2O_8$: C, 57.69; H, 4.84; N, 6.73. Found: C, 57.80; H, 4.94; N, 6.73.

4.2.9. 2,3-Dimethyl-1,4-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (12b). Yellow crystalline solid (89%): mp >220°C (DMF, decomp.); IR (KBr): 1674, 1730, 3186, 3256 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.77 (s, 12H), 2.39 (s, 6H), 7.29 (s, 2H), 8.58 (d, *J*=13.9 Hz, 2H), 11.51 (d, *J*=13.9 Hz, 2H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 14.8, 27.7, 88.5, 105.9, 117.0, 129.8, 136.1, 154.0, 163.9, 166.5; MS (EI) 240 (base peak), 444

($M^{+\cdot}$). Anal. calcd for $C_{22}H_{24}N_2O_8$: C, 59.45; H, 5.44; N, 6.30. Found: C, 59.22; H, 5.73; N, 6.41.

4.2.10. 2,5-Dimethyl-1,4-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (17a). Yellow crystalline solid (55%): mp >262°C (DMF, decomp.); IR (KBr): 1670, 1726, 3164 cm^{-1}; ^1H NMR (CF_3COOD, 200 MHz) δ 1.75 (s,12H), 2.41 (s, 6H), 7.41 (s, 2H), 8.81 (d, J=14.6 Hz, 2H), 11.47 (d, J=14.6 Hz, 2H); ^{13}C NMR (CF_3COOD, 50 MHz) δ 16.2, 25.9, 86.6, 109.4, 121.1, 127.2, 136.3, 155.7 169.3, 169.6; MS (EI) 444 ($M^{+\cdot}$). Anal. calcd for $C_{22}H_{24}N_2O_8$: C, 59.45; H, 5.44; N, 6.30. Found: C, 59.49; H, 5.29; N, 6.35.

4.2.11. 2,5-Dichloro-1,4-bis-[(2,2-dimethyl-4,6-dioxo-1,3-dioxan-5-ylidenemethyl)amino]benzene (17b). Yellow crystalline solid (82%): mp >240°C (DMF, decomp.); IR (KBr): 1676, 1728, 3146 cm^{-1}; ^1H NMR (CF_3COOD, 200 MHz) δ 1.75 (s, 12H), 7.81 (s, 2H), 8.86 (d, J=14.2 Hz, 2H), 11.76 (d, J=14.2 Hz, 2H); ^{13}C NMR (CF_3COOD, 50 MHz) δ 26.0, 88.4, 109.6, 119.9, 126.4, 134.7, 154.6, 168.6, 169.2; MS (EI) 280 (base peak), 282 $(M\text{-}2H)^+$. Anal. calcd for $C_{20}H_{18}Cl_2N_2O_8$: C, 49.50; H, 3.73; N, 5.77. Found: C, 49.46; H, 3.84; N, 6.10.

4.3. General procedure for the preparation of diazatricycles from phenylenediamine-bis(methylene Meldrum's acid) derivatives

The corresponding bis-adduct **2a**–**f**, **7**, **12a** or **17a** (1 mmol) was refluxed in diphenyl ether (20 mL) for 30 min. In the case of **12b** and **17a**, the reflux time had to be kept below 5 min. The mixture was allowed to cool, the dione precipitated upon the addition of hexanes, filtered, washed with hexanes and added to phosphoryl chloride (4 mL). The resulting mixture was refluxed for 30 min under N_2, poured onto ice and water (40 mL), neutralized with 10% NaOH, extracted with CH_2Cl_2 (3×100 mL) and the combined organic layers dried ($MgSO_4$). Rotary evaporation and chromatography gave the diazatricycles **4a**–**e**, **5**, **9**, **13a**,**b**, **18** and **20a** (or **b**).

4.3.1. 4,7-Dichloro-1,10-phenanthroline (4a).[8] Colourless solid (77%): mp 253°C (EtOAc); R_f 0.17 (EtOAc); IR (nujol): 876, 1081, 1217, 1544, 1574 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 7.70 (d, J=4.8 Hz, 2H), 8.24 (s, 2H), 9.06 (d, J=4.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 123.1, 123.8, 126.7, 142.8, 146.9, 150.2; MS (EI) 248 ($M^{+\cdot}$); HRMS (EI) calcd for $C_{12}H_6Cl_2N_2$: ($M^{+\cdot}$) 247.9908, found ($M^{+\cdot}$) 247.9915. Anal. calcd for $C_{12}H_6Cl_2N_2$: C, 57.86; H, 2.43; N, 11.25. Found: C, 57.94; H, 2.40; N, 11.59.

4.3.2. 4,5,7-Trichloro-1,10-phenanthroline (4b). Yellow solid (34%): mp >200°C (EtOAc, decomp.); R_f 0.17 (EtOAc); IR (nujol): 878, 944, 1087, 1233, 1568, 1594 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 7.72 (d, J= 4.8 Hz, 2H), 8.26 (s, 1H), 9.00 (d, J=4.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ 124.5, 125.6, 126.1, 127.4, 129.7, 141.5, 142.4, 146.1, 148.7, 150.2, 150.5; MS (EI) 283 ($M^{+\cdot}$); HRMS (EI) calcd for $C_{12}H_5Cl_3N_2$: ($M^{+\cdot}$) 281.9518, found ($M^{+\cdot}$) 281.9522. Anal. calcd for $C_{12}H_5Cl_3N_2$: C, 50.83; H, 1.78. Found: C, 51.17; H, 2.07.

4.3.3. 4,7-Dichloro-5-methyl-1,10-phenanthroline (4c). Yellow solid (35%): mp >180°C (EtOAc, decomp.); R_f 0.18 (EtOAc); IR (nujol): 869, 1085, 1210, 1551, 1570, 1686 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 3.10 (s, 3H), 7.69 (d, J=4.8 Hz, 2H), 7.99 (s, 1H), 9.00 (d, J=4.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ 26.4, 124.0, 124.8, 126.4, 127.1, 134.8, 141.8, 143.0, 146.1, 147.2, 148.2, 149.4; MS (EI) 263 ($M^{+\cdot}$); HRMS (EI) calcd for $C_{13}H_8Cl_2N_2$: ($M^{+\cdot}$) 262.0065, found ($M^{+\cdot}$) 262.0059. Anal. calcd for $C_{13}H_8Cl_2N_2$: C, 59.34; H, 3.06; N, 10.65. Found: C, 59.32; H, 3.25; N, 10.28.

4.3.4. 4,7-Dichloro-5,6-dimethyl-1,10-phenanthroline (4d). Yellow solid (33%): mp >180°C (EtOAc, decomp.); R_f 0.18 (EtOAc); IR (nujol): 872, 1084, 1221, 1555, 1569, 1682 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 2.90 (s, 6H), 7.62 (d, J=4.8 Hz, 2H), 8.90 (d, J=4.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 67.8 MHz) δ 20.8, 126.6, 127.6, 132.1, 146.2, 147.1, 148.3; MS (EI) 277 ($M^{+\cdot}$); HRMS (EI) calcd for $C_{14}H_{10}Cl_2N_2$: ($M^{+\cdot}$) 276.0221, found ($M^{+\cdot}$) 276. 0219.

4.3.5. 4,7-Dichloro-5,6-dimethoxy-1,10-phenanthroline (4e). Yellow solid (32%): mp 216°C (EtOAc); R_f 0.12 (EtOAc); IR (nujol): 969, 1078, 1292, 1539, 1588 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 4.40 (s, 6H), 7.72 (d, J=4.8 Hz, 2H), 8.98 (d, J=4.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 61.4, 126.7, 127.6, 128.5, 139.7, 146.7, 148.9; MS (EI) 309 ($M^{+\cdot}$). Anal. calcd for $C_{14}H_{10}Cl_2N_2O_2$: C, 54.39; H, 3.26; N, 9.06. Found: C, 54.60; H, 3.13; N, 8.97.

4.3.6. 4,7-Dibromo-1,10-phenanthroline (5a).[12] The same procedure as above but heating phenanthrolone **3a** (0.21 g, 1 mmol) in molten phosphoryl bromide (6.0 g, 21 mmol) at 80°C gave compound **5a** (0.19 g, 58%) as a colourless solid: mp >220°C (EtOAc, decomp.); R_f 0.15 (EtOAc); IR (nujol): 1058, 1212, 1414, 1539, 1569 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 7.94 (d, J=4.8 Hz, 2H), 8.28 (s, 2H), 8.96 (d, J=4.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 22.4 MHz) δ 126.2, 127.7, 128.4, 134.4, 146.7, 150.2; MS (EI) 338 ($M^{+\cdot}$). Anal. calcd for $C_{12}H_6Br_2N_2$: C, 42.64; H, 1.79; N, 8.29. Found: C, 42.79; H, 1.70; N, 8.04.

4.3.7. 4,5,10-Trichloro-1,7-phenanthroline (9). Colourless solid (46%): mp 187–190°C (hexane/EtOAc/$CHCl_3$, 4:1:1); IR (KBr): 778, 832, 912, 1146, 1406, 1544 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 7.71 (d, J=4.7 Hz, 2H), 8.22 (s, 1H), 8.81 (d, J=4.7 Hz, 1H), 8.91 (d, J=4.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 122.7, 123.0, 126.0, 126.4, 131.7, 132.9, 141.7, 143.7, 147.3, 148.5, 150.4, 151.0; MS (EI) 282 ($M^{+\cdot}$). Anal. calcd for $C_{12}H_5Cl_3N_2$: C, 50.83; H, 1.78; N, 9.88. Found: C, 50.62; H, 1.73; N, 9.70.

4.3.8. 1,10-Dichloro-4,7-phenanthroline (13a).[3a] Colourless solid (33%): mp 234–236°C (EtOAc), ^1H NMR ($CDCl_3$, 200 MHz) δ 7.57 (d, J=4.8 Hz, 2H), 8.04 (s, 2H), 8.82 (d, J=4.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 122.6, 132.4, 143.0, 149.8, 150.9. Anal. calcd for $C_{12}H_6Cl_2N_2$: C, 57.86; H, 2.43; N, 11.25. Found: C, 57.71; H, 2.53; N, 11.12.

4.3.9. 1,10-Dichloro-5,6-dimethyl-4,7-phenanthroline (13b). Brown solid (78%): mp 172–174°C ($CHCl_3$); IR (KBr): 768, 838, 1326, 1456, 1554 cm^{-1}; ^1H NMR ($CDCl_3$,

200 MHz) δ 2.77 (s, 6H), 7.44 (d, J=4.7 Hz, 2H), 8.77 (d, J=4.7 Hz, 2H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 14.8, 120.9, 121.3, 136.8, 142.4, 148.4, 150.4; ^{13}C NMR (DMSO-d_6, 50 MHz) δ 14.4, 119.9, 121.6, 136.4, 141.5, 149.4, 149.5; MS (EI) 276 ($M^{+\cdot}$). Anal. calcd for $C_{14}H_{10}Cl_2N_2$: C, 60.67; H, 3.64; N, 10.11. Found: C, 60.83; H, 3.58; N, 10.08.

4.3.10. 4,9-Dichloro-5,10-dimethyl-pyrido[2,3-*g*]quinoline (18). Yellow solid (37%): mp 224°C (CH_2Cl_2/hexane, 3:1); IR (KBr): 700, 848, 886, 1376, 1512 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 3.56 (s, 6H), 7.53 (d, J=4.1 Hz, 2H), 8.82 (d, J=4.1 Hz, 2H); ^{13}C NMR (DMSO-d_6, 50 MHz) δ 16.2, 126.2, 129.3, 138.2, 148.6, 160.7; MS (EI) 276 ($M^{+\cdot}$). HRMS (EI) calcd for $C_{14}H_{10}Cl_2N_2$: ($M^{+\cdot}$) 276.0221, found ($M^{+\cdot}$) 276.0222. Anal. calcd for $C_{14}H_{10}Cl_2N_2$: C, 60.67; H, 3.64; N, 10.11. Found: C, 60.96; H, 3.52; N, 10.56.

4.3.11. 1,2,5,10-Tetrachloro-4,7-phenanthroline (20a) or 1,2,6,10-tetrachloro-4,7-phenanthroline (20b). Bright yellow solid (40%): mp 157–159°C (hexane/CH_2Cl_2/EtOAc, 4:1:1); IR (KBr): 788, 1216, 1370, 1460, 1556, 1592 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 7.65 (d, J=4.8 Hz, 1H), 8.17 (s, 1H), 8.91 (s, 1H), 8.95 (d, J=4.8 Hz, 1H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 122.5, 123.2, 123.3, 129.2, 131.2, 135.9, 139.9, 143.5, 147.0, 147.6, 149.98, 150.01. Anal. calcd for $C_{12}H_4Cl_4N_2$: C, 45.28; H, 1.25; N, 8.80. Found: C, 45.03; H, 1.29; N, 8.80.

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