Regioselective functionalisation of dibenzothiophenes through gold-catalysed intermolecular alkyne oxyarylation†

Matthew J. Barrett, Paul W. Davies* and Richard S. Grainger*

A protocol has been developed for direct Csp³–Csp² bond formation at the 4- and 6-positions of dibenzothiophenes using a gold(1) catalyst with terminal alkynes and dibenzothiophene-S-oxides. The sulfoxide acts as a traceless directing group to avoid the need to prefunctionalise at carbon. The iterative use of this protocol is possible and has been employed in the preparation of novel macrocyclic structures. In addition, a cascade process shows how oxyarylations can be combined with other processes resulting in complex, highly efficient transformations.

Introduction

Dibenzothiophenes are aromatic sulfur-containing heterocycles of broad utility. The optical, redox and conducting properties of dibenzothiophenes and their corresponding S,S-dioxides have led to applications in materials science. S-Substituted dibenzothiophenes are used as precursors to triphenylenes and as a platform for the transfer of reactive species such as F₃C⁺ (Umemoto’s reagent), atomic oxygen (O(3P)), nitrenes and carbenes. Biological and medicinal chemistry applications of dibenzothiophenes and their S-oxides have also been reported.

Functionalised dibenzothiophenes are generally prepared through one of two main approaches. Late stage formation of the dibenzothiophene core has been achieved through intramolecular C–S or C–C (biaryl) bond formation and benzannulation of thiophenes or benzothiophenes. Alternatively, dibenzothiophene undergoes regioselective bromination at the 2,8-positions or the 3,7-positions of the corresponding S,S-dioxide. Substitution at the 4- and 6-positions however requires stoichiometric metallation using organolithium or organoaluminium reagents. Here we report a catalysis-based approach for direct carbon–carbon bond formation at the unfunctionalised 4- and 6-positions of dibenzothiophenes under mild and functional group tolerant conditions.

Our interests in aromatic S-oxide chemistry and π-acid catalysis led us to investigate whether 4-substituted dibenzothiophenes could be accessed in an expedient fashion from dibenzothiophene S-oxides by a gold-catalysed alkyne oxyarylation. This approach should be regiospecific, installing a Csp³–Csp² bond with transfer of the oxygen atom to generate the synthetically versatile α-arylcarbonyl motif (Scheme 1).

Following the introduction of alkyne oxyarylation onto sulfoxides in gold-catalysed intramolecular cycloisomerisations by the groups of Toste and Zhang, the viability of an intermolecular process was shown by Ujaque, Asensio and co-workers (Scheme 2). This and subsequent studies established that such processes are regiospecific by virtue of proceeding via a [3,3]-sigmatropic rearrangement of the vinyl gold carbenoid formed on attack of the sulfoxide to the gold-alkyne complex (Scheme 2, A → C). Despite sulfoxide-based alkyne oxyarylation offering substantial potential for atom-economic, functional group tolerant and direct intermolecular aryl C–H functionalisation routes into challenging aromatic substitution patterns, they have
been rarely employed in synthesis. In large part this can be assigned to the challenges of ensuring that the key aromaticity-disrupting [3,3]-sigmatropic rearrangement (\(B \rightarrow C\)) is favored over elimination of a sulfide nucleofuge (\(B \rightarrow D\)), or competing inter- or intra-molecular attack of a nucleophile (\(B \rightarrow E\)).\(^{17,22,23}\)

In addition, structural elaboration of the sulfoxide must not prevent it from being sufficiently nucleophilic to intercept the alkyne–gold complex A, yet not force further reaction at B to afford the biscarbonyl G alongside two equivalents of sulfide.\(^{24,25}\)

## Results and discussion

The viability of selective elaboration of a dibenzothiophene through an alkyne oxyarylation approach was investigated using dibenzothiophene-S-oxide 1 and hex-1-yne 2a. Applying the combination of Ph₃PAuCl/AgSbF₆ in superheated CH₂Cl₂ from Asensio’s work\(^{17c}\) generated a mixture of dibenzothiophenes 3a and 4 in high yield with the desired oxyarylation product 3a as the minor component (Table 1, entry 1).

An investigation of the reaction conditions was undertaken to explore the factors favouring the rearrangement pathway over those leading to S–O bond cleavage and formation of 4 (Table 1). The most significant factors identified in this study proved to be the use of electron-deficient rather than electron-rich ligands on gold (compare entries 7 and 10 vs. 4, 8 and 9) and the use of lower reaction temperatures (compare entries 13 and 14 vs. 11 and 1), which differ substantially from those conditions previously reported for the intermolecular oxyarylation reaction with sulfoxides.\(^{17c,d}\) These observations are in keeping with higher temperature and electron-density at the gold centre being likely to increase the rate of elimination of the sulfide nucleofuge (Scheme 2, \(B \rightarrow D\)).\(^{26,27}\)

### Table 1 Study of the reaction conditions for oxyarylation using dibenzothiophene-S-oxide\(^{a}\)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Gold catalyst</th>
<th>Solvent</th>
<th>Time/h</th>
<th>Temp/°C</th>
<th>Conc. M</th>
<th>Yield (^{b}/%)</th>
<th>Yield 3a(^{b}/%)</th>
<th>Yield 4(^{b}/%)</th>
<th>Ratio 3a : 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{b})</td>
<td>Ph₃PAuCl/AgSbF₆(^{e})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>0</td>
<td>37</td>
<td>61</td>
<td>1 : 1.6</td>
</tr>
<tr>
<td>2</td>
<td>Ph₃PAuCl/AgSbF₆(^{e})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>10(^{d})</td>
<td>20</td>
<td>30(^{d})</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>Ph₃PAuCl/AgSbF₆(^{e})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>0</td>
<td>39</td>
<td>36</td>
<td>1.1 : 1</td>
</tr>
<tr>
<td>4</td>
<td>Ph₃PAuCl/AgOTs(^{e})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>12</td>
<td>41</td>
<td>31</td>
<td>1.3 : 1</td>
</tr>
<tr>
<td>5</td>
<td>AuCl</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>52</td>
<td>4</td>
<td>22</td>
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<tr>
<td>6</td>
<td>AuPicolinateCl(_{2})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>36</td>
<td>4</td>
<td>24</td>
<td>1 : 6.0</td>
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<tr>
<td>7</td>
<td>((p,FCC(_{6})H₁₃))PAuCl/AgOTs(^{e})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>5</td>
<td>42</td>
<td>24</td>
<td>1 : 8.0</td>
</tr>
<tr>
<td>8</td>
<td>XPhosAuCl/AgOTs(^{e})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>51</td>
<td>10</td>
<td>24</td>
<td>1 : 2.4</td>
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<td>9</td>
<td>JohnPhosAuCl/AgOTs(^{e})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>52</td>
<td>8</td>
<td>24</td>
<td>1 : 3.0</td>
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<tr>
<td>10</td>
<td>(ArO)₃PAuCl/AgOTs(^{e})</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>&lt;5</td>
<td>47</td>
<td>17</td>
<td>2 : 8.1</td>
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<tr>
<td>11</td>
<td>(ArO)₃PAu(NCC₃H₃)SbF₆</td>
<td>CH₂Cl₂</td>
<td>16</td>
<td>70</td>
<td>1.0</td>
<td>&lt;5</td>
<td>48</td>
<td>16</td>
<td>3 : 0.1</td>
</tr>
<tr>
<td>12</td>
<td>(ArO)₃PAu(NCC₃H₃)SbF₆</td>
<td>CH₂Cl₂</td>
<td>3</td>
<td>70</td>
<td>0.1</td>
<td>&lt;5</td>
<td>44</td>
<td>20</td>
<td>2 : 2.1</td>
</tr>
<tr>
<td>13</td>
<td>(ArO)₃PAu(NCC₃H₃)SbF₆</td>
<td>CH₂Cl₂</td>
<td>3</td>
<td>RT</td>
<td>0.1</td>
<td>8</td>
<td>67</td>
<td>10</td>
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<td>14</td>
<td>(ArO)₃PAu(NCC₃H₃)SbF₆</td>
<td>CH₂Cl₂</td>
<td>3</td>
<td>RT</td>
<td>0.1</td>
<td>&lt;5</td>
<td>54</td>
<td>14</td>
<td>3 : 9 : 1</td>
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<tr>
<td>15</td>
<td>(ArO)₃PAu(NCC₃H₃)SbF₆</td>
<td>CH₂Cl₂</td>
<td>3</td>
<td>RT</td>
<td>0.1</td>
<td>29</td>
<td>17</td>
<td>5</td>
<td>3 : 4 : 1</td>
</tr>
<tr>
<td>16</td>
<td>(ArO)₃PAu(NCC₃H₃)SbF₆</td>
<td>Toluene</td>
<td>3</td>
<td>RT</td>
<td>0.1</td>
<td>0</td>
<td>84</td>
<td>8</td>
<td>10 : 5 : 1</td>
</tr>
<tr>
<td>17</td>
<td>(ArO)₃PAu(NCC₃H₃)SbF₆</td>
<td>Toluene</td>
<td>3</td>
<td>0</td>
<td>0.1</td>
<td>0</td>
<td>91</td>
<td>8</td>
<td>11 : 4 : 1</td>
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</table>

\(^{a}\) 1 (0.10 mmol), 2a (0.20 mmol), \(^{b}\) Yields calculated by \(^{1}H\)-NMR spectroscopy against a known quantity of internal standard (1,2,4,5-tetramethylbenzene). \(^{c}\) Catalyst prepared by \(in situ\) combination of equimolar quantity of the (Ligand)AuCl with the appropriate Ag(counterion) salt. \(^{d}\) Due to overlap with unidentified resonances estimated yields were determined. XPhos = 2-dicyclohexylphosphino-2,4,6-triisopropylbiphenyl; JohnPhos = (2-biphenyl)di-tert-butylphosphine; Ar = (2,4-di-tert-butylphenyl).
Little counterion effect was observed and similar results were obtained with the single component catalyst system (entries 10 and 11). Re-evaluating the solvent showed CH2Cl2 to be poor and that excellent selectivity was ultimately obtained in toluene at 0 °C using (2,4-di-tert-butylcyclohexa-2,5-diene)3PAu(NCCH3)SbF6,16 affording 3a in high yield (entry 17).

The use of dibenzothiophene-S-oxide 1 with different terminal alkynes 2b-k was then studied in the oxyarylation reaction: chloro, aryl, vinyl and phthalimide substituents were well-tolerated as were the methyl and silyl-ethers, affording products 3b-k in generally good yields (Table 2, entries 2-7).29 The α-hydroxyketone oxyarylation product 3g was also formed in high yield (entry 8) despite the potential for oxetan-3-one formation by intramolecular capture of the vinylgold intermediate by the propargylic alcohol, as reported using cationic gold(i) catalysts and pyridine-N-oxides.30 This protocol proved to be robust: a very similar yield was obtained even when the reaction was run open to the air and using non-dried toluene with only 1 mol% catalyst loading on larger scale (entries 4 and 5).

The use of phenyl acetylene gave lower yields and led to formation of significant quantities of dibenzothiophene 4 under the standard conditions (Table 2, entry 9). Further reducing the temperature, which in-turn necessitated a higher dilution to maintain solubility of 1, gave improved yields which were also seen with other aryl alkynes, including thiophene and o-bromobenzene (entries 10-13).

The 2,8-dibromo substitution pattern, which is useful for further transformations in materials science applications,4 was readily accommodated with S-oxide 5 reacting to afford the oxyarylation product 6 in good yield (Scheme 3).

The use of an ynamide under these reaction conditions did not lead cleanly to the oxyarylation products, though the complex mixture formed did indicate that 1 was functioning as an effective oxidant. In order to benchmark the potential suitability of dibenzothiophene-S-oxide as an oxidant in gold catalysis it was applied under the conditions previously reported by Davies and co-workers for the oxidative transformation of ynamides using pyridine-N-oxides (Scheme 4).31 Under those conditions 1 proved to be as, or more-, effective than the unsubstituted pyridine-N-oxide and substantially more effective than the diphenylsulfoxide in both the oxidative formation of α,β-unsaturated imide 8 and α-oxoimide 10. Hence 1 may be considered as an alternative reagent to diphenylsulfoxide in gold-catalysed oxidative processes.32,33

Toste and co-workers had previously reported that the gold-catalysed reaction of 1,6-ynes in the presence of excess diphenylsulfoxide led to the formation of aldehydes by intramolecular cyclisation and capture of the intermediate cyclopropyl gold carbene with sulfoxide.25 Given the higher reactivity observed of 1 compared to diphenylsulfoxide (Scheme 4), the reaction of enyne substrates 11 was studied to see whether 1 would be sufficiently nucleophilic to allow the intermolecular reaction of the sulfoxide at the gold-alkyne complex to compete with intramolecular cycloisomerisation.

Table 2  Selective formation of C-4 substituted dibenzothiophenes using different alkynes

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>Cond.</th>
<th>Mmol</th>
<th>Cat./mol%</th>
<th>Time/ h</th>
<th>Yield/ %</th>
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<tr>
<td>1</td>
<td>°Bu</td>
<td>A</td>
<td>0.2</td>
<td>5</td>
<td>0.75</td>
<td>87</td>
</tr>
<tr>
<td>2</td>
<td>(CH3)2Cl</td>
<td>A</td>
<td>0.2</td>
<td>5</td>
<td>0.75</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
<td>(CH3)2Ph</td>
<td>A</td>
<td>0.2</td>
<td>5</td>
<td>0.75</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>CH3O Me</td>
<td>A</td>
<td>0.2</td>
<td>5</td>
<td>0.75</td>
<td>87</td>
</tr>
<tr>
<td>5</td>
<td>CH2O Me</td>
<td>A</td>
<td>2.0</td>
<td>2</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>(CH3)2OTBDPS</td>
<td>A</td>
<td>0.5</td>
<td>2</td>
<td>82</td>
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<tr>
<td>7</td>
<td>CH3NPhth</td>
<td>A</td>
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<tr>
<td>8</td>
<td>CH(OH)C6H4</td>
<td>A</td>
<td>0.2</td>
<td>20b</td>
<td>76</td>
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</tr>
<tr>
<td>9</td>
<td>Ph</td>
<td>A</td>
<td>0.1</td>
<td>5</td>
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<td>48</td>
</tr>
<tr>
<td>10</td>
<td>Ph</td>
<td>B</td>
<td>0.3</td>
<td>5</td>
<td>20</td>
<td>58</td>
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<tr>
<td>11</td>
<td>2-BrC6H4</td>
<td>B</td>
<td>0.2</td>
<td>20</td>
<td>40</td>
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<td>12</td>
<td>4-MeOC6H4</td>
<td>B</td>
<td>0.2</td>
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<td>13</td>
<td>2-Thienyl</td>
<td>B</td>
<td>0.2</td>
<td>20</td>
<td>62</td>
<td></td>
</tr>
</tbody>
</table>

S 2b-k

Scheme 3 Use of substituted dibenzothiophene S-oxide.

Scheme 4 Comparison of reactivity in oxidative transformation of ynamides. Yield of known compounds 8 and 10 determined by 1H NMR against an internal standard.
Under our standard conditions the 1,6-enynes 11a and 11c reacted cleanly to give the oxyarylation products 12a/c in high yield (Scheme 5). In contrast, the cinnamyl derivative 11b and the malonate-derived enyne 11d led to the aldehydes 13b/d with low conversion. On this basis, the relatively high efficacy of dibenzothiophene S-oxide 1 as a nucleophile towards gold alkyne complexes allows it to compete with an intramolecular enyne cycloisomerisation so long as the latter pathway is not strongly biased toward cyclisation by reactive rotamer effects or use of more electron-rich alkenes. Products arising from capture of the vinyl gold carbenoid by the tethered alkene were not observed.34

Iterative application of the oxyarylation reaction was then tested to selectively functionalise both the 4- and 6-positions of dibenzothiophene (Scheme 5). The gold-catalysed reactions of 14, from selective oxidation of 12a using MCPBA,35 with 1,6- and 1,7-enynes 11a and 15 afforded high yields of the 4,6-disubstituted dibenzothiophenes 16a/b respectively. A similar iterative process was also successfully applied to 3d (see ESI† for details). While a higher catalyst loading and dilution were required for the second iteration, the compatibility of this approach with the flanking alkene and keto-functionality highlights the potential of using intermolecular oxyarylation approaches with substantially more-functionalised sulfoxides.

Ring-closing metathesis of dienes 16a/b furnished the new symmetrical and unsymmetrical macrocyclic products 17a/b in good yield, isolated as trans double bond isomers. The double bond geometry in 17a was determined to be trans through X-ray crystallography (Fig. 1).‡

In addition to regiospecific formation of the Csp2–Csp3 bond the simultaneous installation of a methylene carbonyl moiety introduces a potentially useful handle for elaboration. We explored this in two ways: first, a classical Fischer-indole synthesis from 3h (yield unoptimised, Scheme 6) afforded the dibenzothienylindole 18. Thus an alternative is proffered to the standard cross-coupling strategies requiring prefunctionalisation of substrates for the formation of biaryl-
linkages at the 4-position of dibenzothiophene. Second, a cascade process using 1,6-diyne 19 provides direct access into the α-arylated cyclohexenone 20 in a single step (Scheme 6). Gold-catalysed cycloisomerisation of the 1,5-ketoalkyne generated from intermolecular oxyarylation results in formation of five new bonds across the alkyn e including three carbon–carbon bonds at one carbon. The formation of bisketone 21 as a side-product alongside the major product 20 is consistent with the hydration/aldol dehydration pathway Davies and Detty-Mambo previously reported in cycloisomerisation of alkynes tethered to unactivated, enolisable ketones in the presence of cationic gold(i) species.36

Conclusions

Conditions have been developed for regioselective formation of Csp2–Csp3 bonds at the 4- and 6-positions of dibenzothiophenes without prior C-functionalisation. Selectivity for the oxyarylation pathway is favoured by lower temperature and electron-poor ligands on gold. The reactions allow for the introduction of a variety of functionality under robust, scalable conditions. Substantially more elaborate aryl sulfoxides can be used in the oxyarylation approach as demonstrated in an iterative application, in which in conjunction with enyne substrates was used to access new macrocyclic structures. In addition, the use of the oxyarylation reaction as the basis for further cascade process development has been demonstrated.

Experimental†

General oxyarylation procedure 1 (GP1), Table 2, conditions A

The dibenzothiophene-S-oxide (1 eq.) and alkyne (2 eq.) were stirred in toluene (0.1 M) until dissolved. The mixture was then cooled in an ice bath at 0 °C and the catalyst, (2,4-di-tert-butylC₆H₄O)₃PAu(NCCH₃)SbF₆ (1–5 mol%), was added. The reaction mixture was stirred for 6 hours at this temperature and then allowed to warm to stir at rt for 14 hours, filtered through a pad of silica washing with CH₂Cl₂ before being concentrated and the residue purified by column chromatography.

General oxyarylation procedure 2 (GP2), Table 2, conditions B

The dibenzothiophene-S-oxide (1 eq.) and alkyne (2 eq.) were stirred in toluene (0.01 M) until dissolved. The mixture was then cooled in a (NaCl/ice) bath to −10 °C and the catalyst, (2,4-di-tert-butylC₆H₄O)₃PAu(NCCH₃)SbF₆ (5 mol%) was added. The reaction mixture was stirred for 6 hours at this temperature and then allowed to warm to stir at rt for 14 hours, filtered through a pad of silica washing with CH₂Cl₂ before being concentrated and the residue purified by column chromatography.

Alkynes 11a, 3-(prop-2-yn-1-yl oxy)prop-1-ene (54 wt% in Et₂O), and 15, 4-(prop-2-yn-1-yl oxy)but-1-ene (77 wt% in Et₂O), were both used with a diethyl ether impurity.

1-(Dibenzo[b,d]thiophen-4-yl)hexan-2-one (3a)

Prepared according to GP1 using dibenzothiophene-S-oxide 1 (40.0 mg, 0.2 mmol), 1-hexyne (23 µL, 0.4 mmol), toluene (2 mL) and catalyst (11.2 mg, 0.02 mmol, 5 mol%). The reaction was stirred for 45 minutes at 0 °C. Column chromatography (1:19 EtOAc : hexane) afforded 3a (49 mg, 87%) as a white solid; Rₜ 0.28 (1:19 EtOAc : hexane); mp: 43–45 °C; 1H-NMR (300 MHz, CDCl₃): δ = 8.20–8.13 (m, 1H), 8.10 (d, J 7.2, 1H), 7.92–7.82 (m, 1H), 7.51–7.43 (m, 3H), 7.32 (d, J 7.2, 1H), 3.96 (s, 2H), 2.51 (t, J 7.4, 2H), 1.63–1.50 (m, 2H), 1.33–1.19 (m, 2H), 0.85 (t, J 7.3, 3H); 13C-NMR (101 MHz, CDCl₃): δ = 207.5 (C), 140.0 (C), 139.1 (C), 136.1 (C), 136.0 (C), 129.2 (C), 128.0 (CH), 127.0 (CH), 125.2 (CH), 124.7 (CH), 123.0 (CH), 122.0 (CH), 120.6 (CH), 49.4 (CH₂), 42.0 (CH₂), 26.0 (CH₃), 22.3 (CH₃), 14.0 (CH₃); IR (neat): ν = 3057, 2957, 2930, 2872, 1708, 1584, 1404, 749; HR-MS (ES-TOF): m/z: calc'd for C₁₉H₁₈ONaS: 305.0976, found 305.0978 [M + Na]⁺.

6-Chloro-1-(dibenzo[b,d]thiophen-4-yl)hexan-2-one (3b)

Prepared according to GP1 using dibenzothiophene-S-oxide 1 (40.0 mg, 0.2 mmol), 6-chloro-1-hexyne (48.5 µL, 0.4 mmol), toluene (2 mL) and catalyst (11.2 mg, 0.02 mmol, 5 mol%). The reaction was stirred for 45 minutes at 0 °C. Column chromatography (9:11 CH₂Cl₂ : hexane) afforded 3b as a yellow oil (50 mg, 79%); Rₜ 0.44 (9:11 CH₂Cl₂ : hexane); 1H-NMR (300 MHz, CDCl₃): δ = 8.18–8.12 (m, 1H), 8.09 (dd, J 7.9 and 0.9, 1H), 7.91–7.83 (m, 1H), 7.54–7.42 (m, 3H), 7.32 (d, J 7.2, 1H), 3.95 (s, 2H), 3.50–3.42 (m, 2H), 2.59–2.50 (m, 2H), 1.76–1.66 (m, 4H); 13C-NMR (101 MHz, CDCl₃): δ = 206.6 (C), 139.9 (C), 139.0 (C), 136.2 (C), 136.1 (C), 129.0 (C), 128.0 (CH), 127.0 (CH), 125.2 (CH), 124.8 (CH), 123.0 (CH), 122.0 (CH), 120.7 (CH), 49.4 (CH₂), 44.7 (CH₃), 41.1 (CH₂), 31.8 (CH₃), 21.1 (CH₂); IR (neat): ν = 3060, 2953, 1715, 1584, 1443, 1401, 749; HR-MS (ES-TOF): m/z: calc'd for C₁₉H₁₄ONaCl: 339.0586, found 339.0574 [M + Na]⁺.

1-(Dibenzo[b,d]thiophen-4-yl)-4-phenylbutan-2-one (3c)

Prepared according to GP1 using dibenzothiophene-S-oxide 1 (40.0 mg, 0.2 mmol), 4-phenyl-1-butyne (56 µL, 0.4 mmol), toluene (2 mL) and catalyst (11.2 mg, 0.02 mmol, 5 mol%). The reaction was stirred for 45 minutes at 0 °C. Column chromatography (1:1 hexane : CH₂Cl₂) afforded 3c (43 mg, 65%) as a white solid; Rₜ 0.78 (3:7 EtOAc : hexane); mp: 102–104 °C; 1H-NMR (300 MHz, CDCl₃): δ = 8.04–7.96 (m, 1H), 7.93 (d, J 7.8, 1H), 7.74–7.66 (m, 1H), 7.38–7.26 (m, 3H), 7.15–6.93 (m, 6H), 3.78 (s, 2H), 2.79–2.63 (m, 4H); 13C-NMR (101 MHz, CDCl₃): δ = 206.3 (C), 140.9 (C), 140.0 (C), 139.0 (C), 136.2 (C), 136.1 (C), 128.9 (C), 128.6 (2CH), 128.5 (2CH), 128.0 (CH), 127.0 (CH), 126.2 (CH), 125.2 (CH), 124.7 (CH), 123.0 (CH), 122.0 (CH), 120.7 (CH), 49.6 (CH₂), 43.7 (CH₃), 29.9 (CH₃); IR (neat): ν = 3058, 2957, 2877, 1706, 1601, 1583, 1403, 1046, 746; HR-MS (ES-TOF): m/z: calc'd for C₂₃H₂₄ONaS: 353.0976, found 353.0991 [M + Na]⁺.

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1-(Dibenzo[b,d]thiophen-4-yl)-3-methoxypropan-2-one (3d)
Prepared according to GP1 using dibenzothiophene-S-oxide 1 (40.0 mg, 0.2 mmol), methyl propargyl ether (33.8 μl, 0.4 mmol), toluene (2 mL) and catalyst (11.2 mg, 0.02 mmol, 5 mol%). The reaction was stirred for 45 minutes at 0 °C. Column chromatography (CH2Cl2) afforded 3d (47 mg, 87%) as a yellow solid; Rf 0.31 (3 : 7 EtOAc : hexane); mp: 51–53 °C; 1H-NMR (300 MHz, CDCl3): δ = 8.20–8.15 (m, 1H), 8.13 (dd, J 7.9 and 1.0, 1H), 7.90–7.85 (m, 1H), 7.85–7.78 (m, 2H), 7.75–7.67 (m, 2H), 7.54–7.44 (m, 3H), 7.40 (d, J 7.3, 1H), 4.56 (s, 2H), 4.11 (s, 2H); 13C-NMR (101 MHz, CDCl3): δ = 199.0 (C), 167.2 (2C), 140.0 (C), 139.0 (C), 136.5 (C), 136.1 (C), 134.2 (CH2), 132.1 (2C), 128.0 (CH), 127.5 (C), 127.2 (CH), 125.4 (CH), 124.8 (CH), 123.6 (2CH), 123.1 (CH), 122.0 (CH), 121.1 (CH), 46.7 (CH3); IR (neat): ν = 2970, 1769, 1735, 1698, 1470, 1067; HR-MS (ES-TOF): m/z: calcd for C33H26O2NaS: 408.0670, found 408.0667 [M + Na]+.

2-(Dibenzo[b,d]thiophen-4-yl)-3-hydroxydecan-2-one (3g)
Prepared according to GP1 using dibenzothiophene-S-oxide 1 (40 mg, 0.2 mmol), dec-1-yn-3-ol (64 µl, 0.4 mmol), toluene (2 mL) and catalyst (11.2 mg, 0.05 mol%) for 4 hours at 0 °C and stirring for a further 16 hours at rt. Purification of the reaction mixture with column chromatography (9 : 1 hexane : EtOAc), followed by recrystallization from hot MeOH afforded 3g (54 mg, 76%); Rf 0.25 (9 : 1 hexane : EtOAc); mp: 52–54 °C; 1H-NMR (300 MHz, CDCl3): δ = 8.21–8.14 (m, 1H), 8.11 (d, J 7.9, 1H), 7.91–7.82 (m, 1H), 7.54–7.43 (m, 3H), 7.33 (d, J 7.2, 1H), 4.38 (dd, J 7.4 and 3.6, 1H), 4.07 (s, 2H), 3.33 (s, 1H), 2.02–1.88 (m, 1H), 1.75–1.62 (m, 1H), 1.59–1.16 (m, 10H), 0.88 (t, J 6.6, 3H); 13C-NMR (101 MHz, CDCl3): δ = 208.9 (C), 139.9 (C), 138.9 (C), 136.3 (C), 136.1 (C), 128.1 (CH), 127.1 (C), 125.2 (CH), 124.7 (CH), 123.0 (CH), 122.0 (CH), 121.5 (CH), 121.0 (CH), 76.4 (CH), 44.3 (CH3), 34.0 (CH3), 31.9 (CH3), 29.5 (CH3), 29.2 (CH2), 24.9 (CH3), 22.8 (CH3), 14.2(CH3); IR (neat): ν = 3446, 2924, 2854, 1714, 1585, 1443, 1402, 1047, 749; HR-MS (ES-TOF): m/z: calcd for C35H30O2NaS: 577.1551, found 577.1565 [M + Na]+.

2-(Dibenzo[b,d]thiophen-4-yl)-1-phenylethanone (3i)
Prepared according to GP1 using dibenzothiophene-S-oxide 1 (60.0 mg, 0.3 mmol), phenylacetylene (65 µl, 0.6 mmol) and toluene (0.01 M, 30 mL) and catalyst (16.8 mg, 0.03 mmol, 5 mol%). Column chromatography (19 : 1 hexane : EtOAc) followed by recrystallization from hot EtOH afforded 3i (53 mg, 58%) as a white solid; Rf 0.33 (19 : 1 hexane : EtOAc); mp: 127–129 °C; 1H-NMR (300 MHz, CDCl3): δ = 8.19–8.12 (m, 1H), 8.12–8.05 (m, 3H), 7.89–7.82 (m, 1H), 7.63–7.54 (m, 1H), 7.52–7.40 (m, 5H), 7.34 (d, J 6.9, 1H), 4.55 (s, 2H); 13C-NMR (101 MHz, CDCl3): δ = 196.4 (C), 139.9 (C), 138.9 (C), 136.3 (C), 136.1 (C), 128.1 (CH), 127.1 (C), 127.1 (CH), 125.2 (CH), 124.8 (CH), 123.0 (CH), 122.0 (CH), 121.0 (CH), 76.4 (CH), 44.3 (CH3), 34.0 (CH3), 31.9 (CH3), 29.5 (CH3), 29.2 (CH2), 24.9 (CH3), 22.8 (CH3), 14.2(CH3); IR (neat): ν = 3056, 2924, 2856, 1658, 1580, 1440, 1206, 908; HR-MS (ES-TOF): m/z: calcd for C22H18O2NaS: 325.0663, found 325.0660 [M + Na]+.

2-(Dibenzo[b,d]thiophen-4-yl)-2-ethynylbenzene (3j)
Prepared according to GP2 using dibenzothiophene-S-oxide 1 (40.0 mg, 0.2 mmol), 1-bromo-2-ethynylbenzene (50 µl, 0.4 mmol), toluene (20 mL, 0.01 mmol) and catalyst (11.2 mg, 0.02 mmol, 5 mol%). Column chromatography (19 : 1 hexane : EtOAc) followed by recrystallization from hot EtOH afforded 3j (30.5 mg, 40%) as white needles; Rf 0.20 (19 : 1 hexane : EtOAc);
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mp: 93–95 °C; 1H-NMR (300 MHz, CDCl₃): δ = 8.18–8.12 (m, 1H), 8.09 (dd, J 7.7 and 1.1, 1H), 7.89–7.82 (m, 1H), 7.64–7.59 (m, 1H), 7.51–7.42 (m, 3H), 7.41–7.35 (m, 2H), 7.35–7.24 (m, 2H), 4.53 (s, 2H), 13C-NMR (101 MHz, CDCl₃): δ = 200.2 (C), 141.4 (C), 140.2 (C), 139.1 (C), 136.2 (C), 136.1 (2C), 133.7 (C), 131.8 (CH), 128.8 (CH), 128.3 (CH), 127.6 (CH), 127.0 (CH), 125.1 (CH), 124.7 (CH), 123.0 (CH), 120.8 (CH), 118.6 (C), 48.7 (CH); IR ( neat): ν = 2940, 2861, 1703, 1591, 1441, 1380, 1365, 1270, 1117, 870, 750; HR-MS (ES-TOF): m/z: calculated for C₁₆H₁₂O₃Na⁺ 308.0302, found 308.0302 [M + H⁺].

1-(Allyloxy)-3-(dibenzo[b,d]thiophen-4-yl)propan-2-one (12a)

Prepared according to GP1 using dibenzothiophene-S-oxide 1 (100 mg, 0.5 mmol), 3-(prop-2-yn-1-yl)oxy-1-propene (111 mg, 0.4 mmol), and catalyst (11.2 mg, 0.02 mmol, 5 mol%). The reaction mixture was stirred for 4 hours at 0 °C and left to warm to rt for a further 16 hours. Column chromatography (CH₂Cl₂) afforded 12a (119 mg, 80%) as a yellow oil; Rf 0.34 (CH₂Cl₂); 1H-NMR (300 MHz, CDCl₃): δ = 8.19–8.14 (m, 1H), 8.10 (dd, J 7.9 and 1.0, 1H), 7.90–7.83 (m, 1H), 7.52–7.43 (m, 3H), 7.35 (d, J 7.2, 1H), 5.89 (ddt, J 17.2, 10.4 and 5.8, 1H), 5.27 (dd, J 17.2 and 1.5, 1H), 5.21 (dd, J 10.4 and 1.5, 1H), 4.18 (s, 2H), 4.06 (s, 2H), 4.04–0.2 (m, 2H); 13C-NMR (101 MHz, CDCl₃): δ = 205.0 (C), 140.0 (C), 136.2 (C), 136.1 (C), 133.8 (CH), 128.3 (C), 128.1 (CH), 127.0 (CH), 125.2 (CH), 124.7 (CH), 123.0 (CH), 122.0 (CH), 114.0 (2CH), 55.6 (CH₃), 44.4 (CH₂); IR ( neat): ν = 2910, 1717, 1593, 1508, 1400, 1167, 751; HR-MS (ES-TOF): m/z: calculated for C₁₈H₁₄O₃SNa⁺ 319.0769, found 319.0775 [M + Na⁺].

N- Allyl-N-(3-(dibenzo[b,d]thiophen-4-yl)-2-oxopropyl)-4-methylbenzenesulfonamide (12c)

Prepared according to GP1 using dibenzothiophene-S-oxide 1 (40 mg, 0.2 mmol), 3-(3-(dibenzo[b,d]thiophen-4-yl)-2-oxopropyl)-N-(3-(dibenzo[b,d]thiophen-4-yl)propan-2-one (12a) (71.6 mg, 0.2 mmol) was added to a 50 mL RBF with methyl propargyl ether (34 µl, 0.4 mmol) and CHCl₃ (28 mg, 42%) as a white solid; Rf 0.47 (28 mg, 42%); 1H-NMR (300 MHz, CDCl₃): δ = 7.93–7.83 (m, 3H), 7.34 (d, J 7.2, 1H), 6.98–6.89 (m, 2H), 4.49 (s, 2H), 3.86 (s, 3H); 13C-NMR (101 MHz, CDCl₃): δ = 195.0 (C), 163.8 (C), 139.8 (C), 139.1 (C), 136.3 (C), 136.2 (C), 131.0 (CH), 129.9 (C), 129.7 (C), 127.8 (CH), 126.9 (CH), 125.1 (CH), 124.7 (CH), 123.0 (CH), 122.0 (CH), 120.4 (CH), 114.0 (2CH), 55.6 (CH₃), 44.4 (CH₂); IR ( neat): ν = 2910, 1717, 1593, 1508, 1400, 1167, 751; HR-MS (ES-TOF): m/z: calculated for C₁₈H₁₄O₃SNa⁺ 319.0769, found 319.0775 [M + Na⁺].

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to rt over 2 hours, washed with NaHCO₃ (4 × 10 mL), extracted with CH₂Cl₂ (4 × 10 mL), dried over Na₂SO₄, filtered and concentrated under reduced pressure. Purification by column chromatography (4 : 1 hexane : EtOAc to EtOAc) afforded firstly 12a (25 mg, 22%) and then 14 (74 mg, 62%) as a white solid; R₈ 0.37 (3 : 7 hexane : EtOAc); mp: 98–100 °C; ¹H-NMR (300 MHz, CDCl₃): δ = 7.96 (d, J 7.5, 1H), 7.80 (d, J 7.6, 1H), 7.74 (d, J 7.5, 1H), 7.64–7.53 (m, 2H), 7.50 (td, J 7.5 and 0.9, 1H), 7.29 (d, J 7.6, 1H), 5.94 (ddt, J 17.2, 10.5 and 5.7, 1H), 5.32 (dd, J 17.2 and 1.5, 1H), 5.24 (dd, J 10.5 and 1.2, 1H), 4.38–4.17 (m, 4H), 4.11 (d, J 5.8, 2H); ¹³C-NMR (101 MHz, CDCl₃): δ = 204.6 (C), 144.7 (C), 144.0 (C), 137.7 (C), 137.3 (C), 135.0 (C), 133.9 (CH), 132.7 (CH), 132.7 (CH), 131.7 (CH), 129.7 (CH), 127.5 (CH), 122.2 (CH), 121.0 (CH), 118.3 (CH₂), 75.1 (CH₂), 72.7 (CH₂), 42.5 (CH₂); IR (neat): ν = 2963, 1720, 1644, 1075, 1054, 762; HR-MS (ES-TOF): m/z: calculated for C₁₈H₁₄O₃S: 313.0896, found 313.0895 [M + H⁺].

Macrocycle 17a

Sulfoxide 14 (68 mg, 0.22 mmol) and enyne 11a (54 wt% in Et₂O, 78.3 mg, 0.44 mmol) were dissolved in toluene (8.8 mL, 0.025 M). After stirring for 20 minutes the reaction mixture was transferred to an ice bath at 0 °C. (2,4-Di-tert-butylcyclohexyl)dichloro(μ-chlorido)[1,3-Bis-(2,4,6-trimethylphenyl)-2-imidazolidinylidene]dichloro(phenylmethylene)(tricyclohexylphosphine)ruthenium (5.0 mg, 0.025 mmol) was added. The reaction was heated to reflux for 20 minutes, concentrated and purified by column chromatography (3 : 7 hexane : EtOAc) to afford 17a (80 mg, 86%) as a white solid; R₈ 0.58 (1 : 1 hexane : EtOAc); mp: 165–167 °C; ¹H-NMR (300 MHz, CDCl₃): δ = 8.08 (d, J 7.2, 2H), 7.48 (app t, J 7.6, 2H), 7.39 (d, J 7.6, 2H), 5.74–5.60 (m, 2H), 4.19 (s, 4H), 4.02 (s, 4H), 3.96 (dd, J 3.0 and 1.3, 4H); ¹³C-NMR (101 MHz, CDCl₃): δ = 205.0 (C), 139.2 (C), 136.7 (C), 136.9 (C), 136.7 (C), 132.0 (C), 131.4 (C), 131.4 (C), 130.2 (C), 128.1 (2C), 126.8 (C), 122.4 (C), 119.0 (C), 119.0 (C), 116.3 (C), 74.8 (CH₂), 72.6 (CH₂), 71.3 (CH₂), 45.6 (CH₂); IR (neat): ν = 2860, 1721, 1644, 1575, 1473, 1061, 913, 776; HR-MS (ES-TOF): m/z: calculated for C₂₅H₂₆O₄NaS: 445.1450, found 445.1429 [M + Na⁺].

Macrocycle 17b

Sulfoxide 14 (60 mg, 0.192 mmol) and enyne 15 (77 wt% in Et₂O, 50 mg, 0.348 mmol) were dissolved in toluene (0.025 M, 10 mL). After stirring for 20 minutes at rt the reaction was transferred to an ice bath at 0 °C and (2,4-di-tert-butylcyclohexyl)dichloro(μ-chlorido)[1,3-Bis-(2,4,6-trimethylphenyl)-2-imidazolidinylidene]dichloro(phenylmethylene)(tricyclohexylphosphine)ruthenium (10.4 mg, 0.02 mmol) was added to a solution of 16a (100 mg, 0.245 mmol) in CH₂Cl₂ (25 mL). The reaction mixture was heated to reflux for 1 hour, allowed to cool, concentrated and purified by column chromatography (3 : 7 hexane : EtOAc) to afford 17b (50 mg, 0.118 mmol) in CH₂Cl₂ (25 mL). The reaction mixture was heated to reflux for 2 hours, concentrated and purified by column chromatography (3 : 7 hexane : EtOAc) to afford 17b (35 mg, 70%) as a white solid; R₈ 0.48 (1 : 1 hexane : EtOAc); mp: 138–139 °C; ¹H-NMR (300 MHz, CDCl₃): δ = 8.07 (d, J 7.8, 2H), 7.48 (td, J 7.6 and 3.1, 2H), 7.37 (d, J 5.1, 2H), 6.11–5.95 (m, 1H), 5.69 (dt, J 15.0 and 5.6, 1H), 4.18 (s, 4H), 4.15–4.05 (m, 6H), 3.64 (t, J 5.8, 2H), 2.42 (dd, J 11.6 and 5.6, 2H); ¹³C-NMR (101 MHz, CDCl₃): δ = 206.6 (C), 205.8 (C), 139.2 (C), 139.1 (C), 136.7 (C), 136.6 (C), 132.0 (C), 128.7 (CH), 128.7 (CH), 128.4 (C), 128.4 (C), 127.4 (CH), 125.4 (2CH), 121.0 (CH), 120.9 (CH), 76.3 (CH₂), 74.4 (CH₂), 71.7 (CH₂), 44.7 (CH₂), 44.2 (CH₂), 32.8 (CH₂); IR (neat): ν = 2861, 1720, 1644, 1575, 1426, 1390, 1331, 1144, 1060, 1045, 913, 776, 731; HR-MS (ES-TOF): m/z: calculated for C₂₅H₂₄O₄NaS: 403.0980, found 403.0996 [M + Na⁺].
was extracted with \( \text{CH}_2\text{Cl}_2 \) (10 mL × 3) and the organic portions were washed with HCl (1 M, 5 mL), water (5 mL), dried over \( \text{Na}_2\text{SO}_4 \), concentrated and purified by column chromatography (9 : 1 hexane : EtOAc) to afford 18 (45.6 mg, 66%) as a viscous orange oil; \( R_F \) 0.31 (9 : 1 hexane : EtOAc); \(^1\)H-NMR (300 MHz, CDCl\(_3\)); \( \delta = 8.46 \) (s, 1H), 8.21 (ddd, \( J = 7.6, 5.6 \) and 1.4, 2H), 7.77–7.70 (m, 1H), 7.59–7.48 (m, 3H), 7.48–7.41 (m, 3H), 7.40–7.34 (m, 2H), 7.33–7.20 (m, 4H), 7.13 (t, \( J = 7.6 \) and 0.9, 1H); \(^1\)C-NMR (101 MHz, CDCl\(_3\)); \( \delta = 141.4 \) (C), 140.1 (C), 136.1 (C), 136.0 (2C), 134.8 (C), 132.5 (C), 130.5 (C), 129.3 (CH), 128.9 (2CH), 128.8 (C), 127.9 (CH), 127.3 (2CH), 126.7 (CH), 125.0 (CH), 124.3 (CH), 123.0 (CH), 122.9 (CH), 121.8 (CH), 120.4 (CH), 120.4 (CH), 120.3 (CH), 113.5 (C), 111.1 (CH); IR (neat): \( \nu = 2960, 2929, 1601, 1460, 1370, 1280, 1111, 754 \). HR-MS (ES-TOF); \( m/z \) calculated for \( \text{C}_{25}\text{H}_{30}\text{NaS} \): 459.1229 [M + Na]+.

Notes and references


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20 In the course of preparing our work for publication, a report appeared which includes one example of an acid catalysed reaction of dibenzo thiophene S-oxide with an amino to provide a C-4 substituted dibenzo thiophene: B. Peng, X. Huang, L.-G. Xie and N. Maulide, Angew. Chem., Int. Ed., 2014, 53, 8718–8721.


27 The role of the phosphite ligand to allow reaction at a vinyl gold carb eno mid centre by disfavouring elimination of a nucleofuge to form the gold carbene centre was employed to rationalise chemoselectivity for intermolecular trapping pathways in gold-catalysed ynamide oxidation reaction. See ref. 16c.


29 The use of hex-1-yn-1-ylbenzene gave the α-β unsaturated ketone in a 58% yield (based on the dibenzo thiophene-S-oxide).


32 See ref. 24 for gold-catalysed double oxidation of triple bonds using diphenylsulfide (4 equiv.) with AuCl/AgSbF6 (4 mol%), under reflux in 1,2-DCE.


35 The use of urea hydrogen peroxide afforded the sulfone preferentially and sodium metaperiodate gave no reaction.