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# An Electrochemical Alternative Approach to the Cyclization of Alkynes Bearing Proximate Malonyl Moieties

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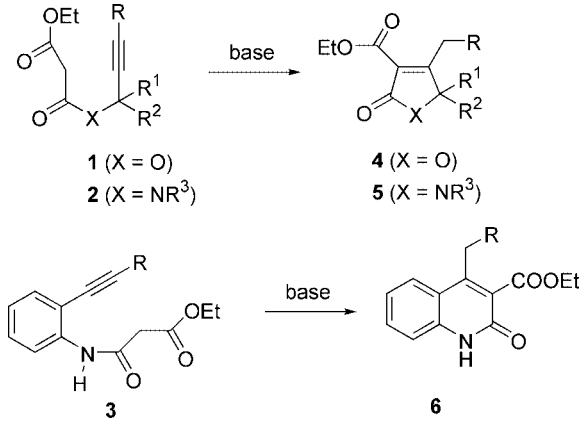
A versatile alternative approach to the synthesis of butenolides, quinolones and 3-pyrrolin-2-ones has been achieved by galvanostatic electrolysis of MeCN/TEATFB solutions and subsequent addition of the cathodic solution to alkynes bearing proximate malonyl moieties. The electrogenerated cyanomethyl anion permits the formation of the reactive anionic intermediates under mild conditions, avoiding the need to use classical bases.


## Introduction

The widespread occurrence of heterocyclic derivatives as main components of substructures of numerous natural products, their presence in the structures of many important pharmaceuticals and their use as building blocks in synthetic chemistry make the development of efficient strategies for the construction of ring systems containing heteroatoms an enduring challenge for organic chemists. The reactions of alkynes are among the most important routes to heterocyclic derivatives.[1] Besides transition metal-catalysed cyclizations of alkynes,[2] the construction of ring systems by intramolecular addition of an anionic centre to a carbon–carbon triple bond has attracted considerable attention in recent years, and the regioselectivity of the process has been investigated.[3] In this field, the use of alkynes bearing proximate pronucleophiles as useful building blocks for the preparation of a variety of heterocycles through regioselective 5-*exo*-*dig*,[4] 6-*exo*-*dig*[5] and 6-*endo*-*dig*[6] base-promoted processes has been reported. This strategy has further advantages because of the easy coupling of terminal alkyne functionality with organic electrophiles, such as aryl halides or vinyl triflates, which generates molecular diversity in the substrates and consequently in the target heterocycles.[7] In particular, the regioselective 5-*exo*-*dig* base-promoted cyclization of alkynes **1** and **2**, each bearing a proximate malonyl moiety (Scheme 1), allowed the preparation of butenolides[8] **4** and 3-pyrrolin-2-ones[9] **5**, respectively, whereas the alkynes **3** underwent regioselective 6-*exo*-*dig* cyclization to give quinolones[10] **6**.




Scheme 1.

Over recent decades, electrochemical technology has emerged as convenient tool for improvement of selectivity, cheapness and eco-friendliness of a wide variety of synthetic processes.[11] Additionally, electrosynthesis can provide a valuable alternative to the use of conventional reagents for fine chemical synthesis.[12] A variety of synthetic targets have been conveniently obtained through the use of electrogenerated bases (EGBs). Among the different EGBs, the electrogenerated cyanomethyl anion,[13] obtained by reduction of MeCN/supporting electrolyte solutions, has proved to be effective for the selective activation of amidic and aminic N–H[14] and C–H bonds.[15] The exploitation of electrochemistry as a tool to generate carbanions, which can

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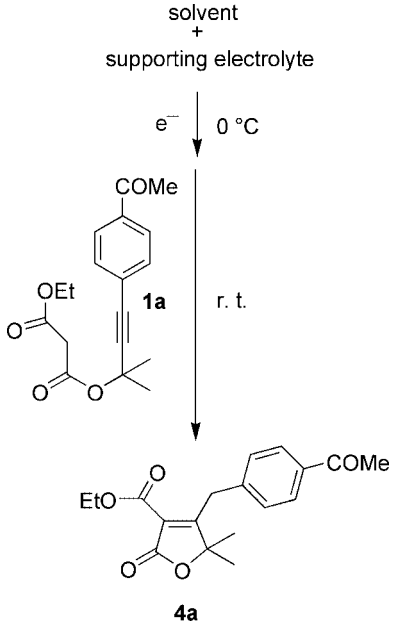
undergo annulation processes through intramolecular nucleophilic attack on carbon–carbon triple bonds, therefore appeared very attractive to us from a synthetic standpoint. Here we report the results of our investigation.

## Results and Discussion

The aim of this study was to achieve an electrochemically induced cyclization of alkynes **1**–**3** under mild conditions, avoiding the use of catalysts and strong bases. In order to verify the efficiency of the electrochemical deprotonation reaction, solutions of various supporting electrolytes in MeCN, EtCN and DMSO were electrolysed at 0 °C under galvanostatic control ($J$ = 20 mA·cm$^{-2}$), in a divided cell with a platinum cathode and anode. At the end of the electrolysis, the model compound **1a** was added to the cathodic solution, the resulting mixture was stirred at room temperature until TLC disappearance of the starting **1a**, and the target butenolide **4a** was isolated by standard workup (Scheme 2; Table 1). The results obtained are summarized in Table 1.




Scheme 2.

Our findings are consistent with a reaction pathway involving the formation of **4a** through a deprotonation reaction of **1a** followed by a 5-*exo*-*dig* cyclization of the corresponding intermediate malonyl anion. The yield of **4a** depends on the amount of the electricity supplied during the electrolyses ($Q$), increasing with $Q$ up to a value of 2.0 F mol$^{-1}$ with reference to substrate **1a**. As reported in our previous works,[13,16] the electrogeneration of the cyanomethyl anion is quite a complex process that also involves the formation of 3-aminocrotonitrile anion (Table 1, Entries 1–3). The solvent and the supporting electrolyte also play a pivotal role in determining the reaction outcome. The best results were observed with use of acetonitrile as solvent and tetraethylammonium tetrafluoroborate (TEATFB) as supporting electrolyte. To ascertain whether this alternative method for synthesis of functionalized butenolides from propargyl ethylmalonates could be generalized, the electrochemically induced cyclization of **1b**–**j** was studied under the reaction conditions given in Entry 5 in Table 1. As can be seen in Table 2, butenolides **4b**–**j** were synthesized in good to excellent yields. The reaction tolerates a wide range of functionalities on the aryl/heteroaryl group bonded to the $C_{sp}$ carbon; moreover, highly efficient cyclization was observed even when the aryl group was replaced by a carboxymethyl substituent (Table 2, Entry 12). The reactions were generally carried out by addition of the alkyne to the catholite at the end of the electrolysis (Procedure A). Alternatively, with the aim of further simplification of the procedure, the electrochemical reduction of the solvent-supporting electrolyte solution can be carried out in the presence of the acetylenic malonate (Procedure B): in this way the target butenolides **4** were isolated in yields either comparable to or lower than those obtained by Procedure A (compare Entries 3–4 of Table 2 with Entries 1–2 and 6–7, respectively). It is worth noting that this new electrochemical approach has the additional advantage of the milder reaction conditions. Unlike the previously developed base-promoted cyclization reaction of propargyl ethylmalonates **1**,[8] the current cyclization reaction can be carried out at room temperature. Only with **1j** did the cyclization only occur in MeCN at reflux, because of its poor solubility at room temperature in MeCN. Very probably, the presence of tetraalkylammoniun cation as a counterion to the naked malonyl anion is responsible for the high reactivity observed under these reaction conditions. The beneficial effect of soft tetraalkylammoniun cations on the cyclization of alkynes bearing proximate nucleophiles has been reported in the literature.[17]

Table 1. Synthesis of **4a** from **1a**.[a]

| Entry | $Q$ (F·mol$^{-1}$)[b] | Solvent | Supporting electrolyte[c] | Product **4a** yield (%)[d] |
|---|---|---|---|---|
| 1 | 1.2 | MeCN | TEAP | 60 |
| 2 | 1.6 | MeCN | TEAP | 74 |
| 3 | 2.0 | MeCN | TEAP | 88 |
| 4 | 2.0 | MeCN | TBAHFP | 78 |
| 5 | 2.0 | MeCN | TEATFB | 94 |
| 6 | 2.0 | MeCN | TEAHFP | 92 |
| 7 | 2.0 | DMSO | TEAP | 40 |
| 8 | 2.0 | DMSO | TEAHFP | 39 |
| 9 | 2.0 | EtCN | TEATFB | 70 |

[a] Electrolyses were carried out at 0 °C in a divided cell (Pt electrodes, $J$ = 20 mA·cm$^{-2}$) with use of 2.0 mmol of supporting electrolyte in 20 mL of catholite, 1.0 mmol of **1a** then being added at room temp. [b] $Q$ is relative to the substrate **1a**. [c] TEAP: tetraethylammonium perchlorate; TBAHFP: tetrabutylammonium hexafluorophosphate; TEATFB: tetraethylammonium tetrafluoroborate; TEAHFP: tetraethylammonium hexafluorophosphate. [d] Yields refer to isolated product **4a**.

We then extended the electrochemically induced cyclization reaction to the preparation of 3-pyrrolin-2-ones **5** and quinolones **6** (Table 3). The *N*-propargylmalonamides **2a**–**b** cyclized either at room temperature or at 80 °C to afford highly substituted 3-pyrrolin-2-ones **5a**–**b** in good yields (Scheme 3).

Table 2. Synthesis of butenolides **4b**–**j** from **1b**–**j**.[a]

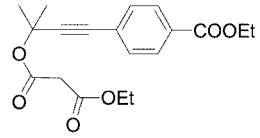
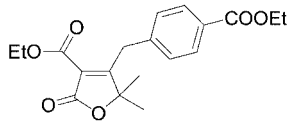
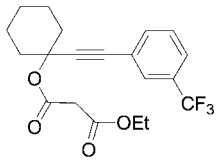
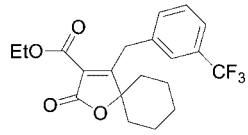
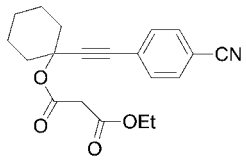
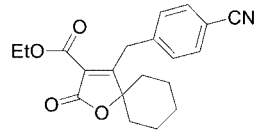
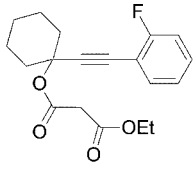
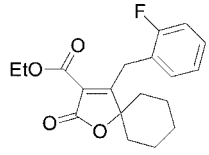
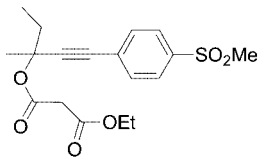
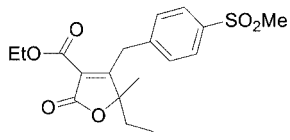
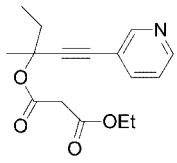
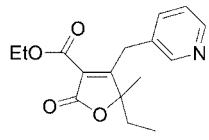
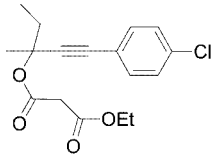
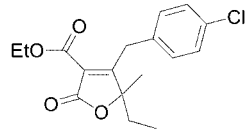
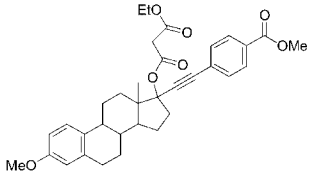
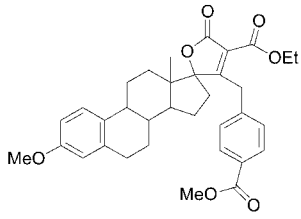
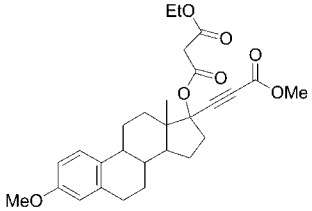
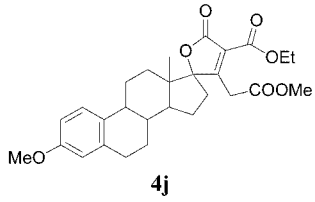
| Entry | Compound **1** | Procedure | Time [h] | Compound **2** | % Yield[b] |
|---|---|---|---|---|---|
| 1 |  **1b** | A | 4 |  **4b** | 82 |
| 2 | **1b** | B | 4 | **4b** | 53 |
| 3 |  **1c** | A | 4 |  **4c** | 93 |
| 4 | **1c** | B | 4 | **4c** | 90 |
| 5 |  **1d** | A | 2 |  **4d** | 92 |
| 6 |  **1e** | A | 3 |  **4e** | 88 |
| 7 | **1e** | B | 3 | **4e** | 70 |
| 8 |  **1f** | A | 3 |  **4f** | 92 |
| 9 |  **1g** | A | 24 |  **4g** | 67 |
| 10 |  **1h** | A | 18 |  **4h** | 84 |

Table 2. *(Continued)*

| Entry | Compound **1** | Procedure | Time [h] | Compound **2** | % Yield[b] |
|---|---|---|---|---|---|
| 11 |  **1i** | A | 4 |  **4i** | 63 |
| 12 |  **1j** | A | 3 |  **4j** | 96[c] |

[a] Procedure A: Electrolyses of MeCN/TEATFB solutions were carried out at 0 °C with use of Q = 2.0 F·mol$^{-1}$ (length of electrolysis: 35 min; $J$ = 20 mA·cm$^{-2}$), after which **1** (0.5 mmol) was added at room temp. Procedure B: electrolyses were carried out at 0 °C in MeCN/TEATFB solutions containing the starting substrate **1** (0.5 mmol) with use of Q = 2.0 F·mol$^{-1}$ (length of electrolysis: 35 min; $J$ = 20 mA·cm$^{-2}$). [b] Yields refer to single runs and are for pure isolated products. [c] **1j** was added to the electrolysed solution and the reaction mixture was heated at 80 °C.

3,4-Disubstituted-2(1*H*)-quinolones **6a**–**b** were also isolated after the electrochemically induced cyclization of the *N*-(*O*-alkynyl)malonamides **3a**–**b** at 80 °C (Scheme 4).

## Conclusions

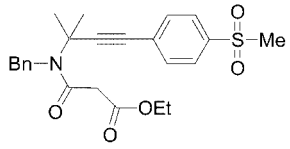
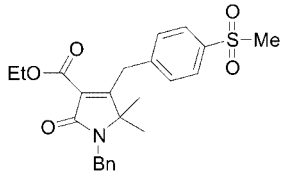
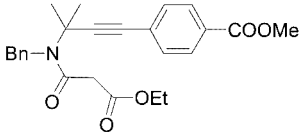
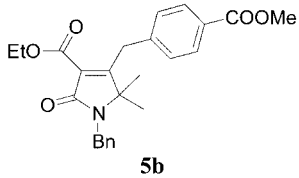
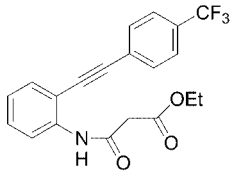
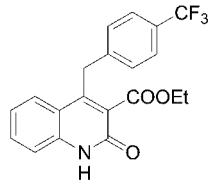
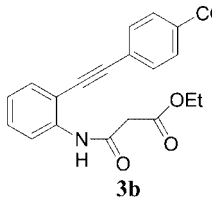
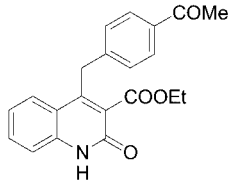
In summary, we have developed a versatile electrochemical approach to the synthesis of functionalized butenolides, 3-pyrrolin-2-ones and quinolones. These derivatives have been synthesized under mild conditions, in good to excellent yields, with the highest yields being observed in MeCN as solvent, TEATFB as supporting electrolyte, and with addition of the acetylenic malonyl derivatives to the cathodic solution after the electrolysis. The use of transition metals catalyst or bases can be eliminated, and the presence of soft tetraalkylammonium cation can offer additional advantage by facilitating the intramolecular nucleophilic attack. With respect to traditional chemical methods, the electrochemical, base-free conditions can provide a viable alternative for the generation of highly reactive carbanions. Further work towards the achievement of carb- and heteroanions by direct cathodic reduction is in progress,[18] in order to avoid the use of supporting electrolytes in the electrolysis medium.

## Experimental Section

**General Remarks:** All starting materials were commercially available and were used as purchased without further purification, unless otherwise stated. Temperatures are reported as bath temperatures. Solvents used in electrolysis were distilled prior to use. Compounds on analytical thin-layer chromatograms (TLC) were viewed by UV light (254 nm) and with iodine and vanillin/sulfuric acid mixtures. The products, after conventional workup, were purified by flash chromatography on silica gel (230–400 mesh) with elution with *n*-hexane/ethyl acetate mixtures. $^1$H NMR and $^{13}$C NMR spectra were recorded in $CDCl_3$ (unless otherwise stated) with a Bruker AC 200 E spectrometer. EI (70 eV) mass spectra were recorded with a Varian Saturn 2100 T GC/MS. IR spectra were recorded with a Perkin–Elmer 683 spectrometer. Only the most significant IR absorptions are given. The alkynes **1j**,[8] **2a**–**b**[9] and **3a**–**b**[10] were prepared as reported in the literature. Analytical data for 3-pyrrolin-2-ones **5a**–**b** were describeL, 3.6 mmol), piperidine (0.326 mL, 3.3 mmol), $Pd(OAc)_2$ (0.013 g, 0.06 mmol) and $PPh_3$ (0.031 g, 0.12 mmol) were added to a solution of 1-ethynylcyclohexanol (0.372 g, 3.0 mmol) in DMF (4.0 mL). The mixture was stirred at 60 °C under $N_2$ for 5 h and was then extracted with HCl (0.1 N, 50 mL) and EtOAc (3 × 50 mL). The combined organic layers were dried with $Na_2SO_4$ and concentrated under reduced pressure, and the residue was dissolved in $CH_2Cl_2$ (5 mL) and cooled in an ice-bath. 2,6-Di-*tert*-butyl-4-methylpyridine (0.922 g, 4.5 mmol) and ethyl malonyl chloride (0.569 mL, 4.5 mmol) were added to the reaction mixture, which was stirred under $N_2$ at 0 °C for 1 h and then at r.t for 1 h, diluted with $Na_2CO_3$ (0.5 M, 50 mL) and extracted with $CH_2Cl_2$ (3 × 25 mL). The combined organic layers were dried with $Na_2SO_4$ and concentrated under reduced pressure. Column chromatographic purification on silica gel (hexane/EtOAc, 98:2, v/v) afforded ethyl 4-({1-[(2-fluorophenyl)ethynyl]cyclohexyl}oxy)-3-oxobutanoate (**1e**, 0.820 g, 82% yield), oil. $^1$H NMR: $\delta$ = 7.70 (s, 1 H), 7.63–7.52 (m, 2 H), 7.46–7.41 (m, 1 H), 4.21 (q, $J$ = 7.1 Hz, 2 H), 3.39 (s, 2 H), 2.25–2.15 (m, 2 H), 2.10–2.00 (m, 2 H), 1.74–1.64 (m, 4 H), 1.60–1.35 (m, 2 H), 1.28 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 166.7 (–COO–), 164.7 (–COO–), 135.2, 131.2 (q, $J$ = 32.6 Hz, $C$CF$_3$), 128.9, 128.7 (q, $J$ = 4.0 Hz), 125.0

Table 3. Synthesis of 3-pyrrolin-2-ones **5** and quinolones **6**.[a]

| Entry | Compound 1 | Temp. [°C] | Time [h] | Compound **2** | % Yield[b] |
|---|---|---|---|---|---|
| 1 |  **2a** | 80 | 1 |  **5a** | 78 |
| 2 |  **2b** | 25 | 1 |  **5b** | 77 |
| 3 |  **3a** | 80 | 16 |  **6a** | 68 |
| 4 |  **3b** | 80 | 16 |  **6b** | 62 |

[a] Electrolyses were carried out by Procedure A at 0 °C in MeCN with TEATFB and use of Q = 2.0 F·mol$^{-1}$, (length of electrolysis: 35 min; $J$ = 20 mA·cm$^{-2}$), after which **2** or **3** (0.5 mmol) was added at the temperature stated. [b] Yields refer to single runs and are for pure isolated products.

(q, $J$ = 3.7 Hz), 123.8 (q, $J$ = 272 Hz, $CF_3$), 123.7, 90.3 (C≡C), 85.0 (C≡C), 77.0, 61.5, 42.5, 36.9, 25.1, 22.5, 14.1 ppm. IR (neat): $\tilde{\nu}$ = 2210, 1730 cm$^{-1}$. MS (EI): *m*/*z* (%): 332 (6) [M]$^+$, 200 (100).

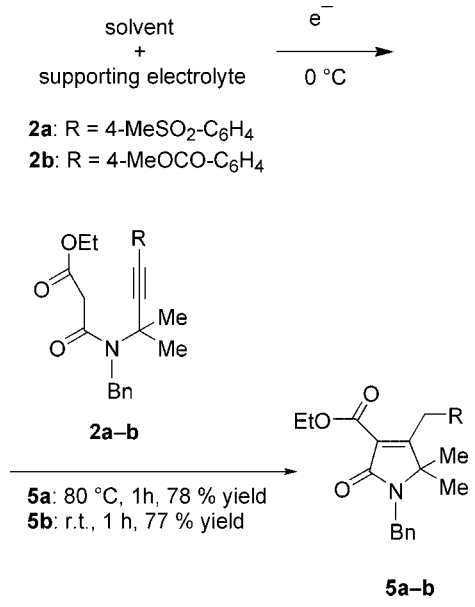
**3-(4-Acetylphenyl)-1,1-dimethylprop-2-ynyl Ethyl Malonate (1a):** 0.618 g, 65% yield, oil. $^1$H NMR: $\delta$ = 7.88 (d, $J$ = 8.2 Hz, 2 H), 7.50 (d, $J$ = 8.2 Hz, 2 H), 4.20 (q, $J$ = 7.1 Hz, 2 H), 3.38 (s, 2 H), 2.58 (s, 3 H), 1.79 (s, 6 H), 1.27 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 197.2 (C=O), 166.5 (–COO–), 164.7 (–COO–), 136.4, 131.9, 128.1, 127.3, 92.8 (C≡C), 83.7 (C≡C), 73.6, 61.4, 42.3, 28.7, 26.6, 14.1 ppm. IR (neat): $\tilde{\nu}$ = 2200, 1730, 1680 cm$^{-1}$. MS (EI): *m*/*z* (%): 316 (11) [M]$^+$, 184 (56), 169 (100).

**3-[4-(Ethoxycarbonyl)phenyl]-1,1-dimethylprop-2-ynyl Ethyl Malonate (1b):** 0.634 g, 61%, oil. $^1$H NMR: $\delta$ = 7.97 (d, $J$ = 8.3 Hz, 2 H), 7.48 (d, $J$ = 8.3 Hz, 2 H), 4.36 (q, $J$ = 7.1 Hz, 2 H), 4.20 (q, $J$ = 7.1 Hz, 2 H), 3.38 (s, 2 H), 1.78 (s, 6 H), 1.38 (t, $J$ = 7.1 Hz, 3 H), 1.27 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 166.5 (–COO–), 165.9 (–COO–), 164.7 (–COO–), 131.6, 130.1, 129.3, 127.1, 92.4 (C≡C), 83.8 (C≡C), 73.6, 61.4, 61.1, 42.3, 28.7, 14.2, 14.1 ppm. IR (neat): $\tilde{\nu}$ = 1740, 1720 cm$^{-1}$. MS (EI): *m*/*z* (%): 346 (5) [M]$^+$, 214 (88), 186 (37), 169 (100).

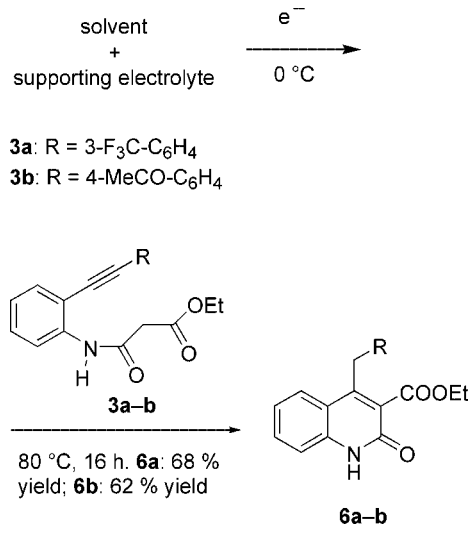
**Ethyl 1-{[3-(Trifluoromethyl)phenyl]ethynyl}cyclohexyl Malonate (1c):** 0.687 g, 60% yield, oil. $^1$H NMR: $\delta$ = 7.70 (s, 1 H), 7.63–7.52 (m, 2 H), 7.46–7.41 (m, 1 H), 4.21 (q, $J$ = 7.1 Hz, 2 H), 3.39 (s, 2 H), 2.25–2.15 (m, 2 H), 2.10–2.00 (m, 2 H), 1.74–1.64 (m, 4 H), 1.60–1.35 (m, 2 H), 1.28 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 166.7 (–COO–), 164.7 (–COO–), 135.2, 131.2 (q, $J$ = 32.6 Hz, $CCF_3$), 128.9, 128.7 (q, $J$ = 4.0 Hz), 125.0 (q, $J$ = 3.7 Hz), 123.8 (q, $J$ = 272 Hz, $CF_3$), 123.7, 90.3 (C≡C), 85.0 (C≡C), 77.0, 61.5, 42.5, 36.9, 25.1, 22.5, 14.1 ppm. IR (neat): $\tilde{\nu}$ = 1740, 1720 cm$^{-1}$. MS (EI): *m*/*z* (%): 382 (11) [M]$^+$, 250 (100).

**1-[(4-Cyanophenyl)ethynyl]cyclohexyl Ethyl Malonate (1d):** 0.681 g, 67% yield, m.p. 44–45 °C. $^1$H NMR: $\delta$ = 7.60 (d, $J$ = 8.4 Hz, 2 H), 7.52 (d, $J$ = 8.4 Hz, 2 H), 4.21 (q, $J$ = 7.1 Hz, 2 H), 3.40 (s, 2 H), 2.27–2.12 (m, 2 H), 2.10–1.95 (m, 2 H), 1.75–1.65 (m, 4 H), 1.60–




Scheme 3.




Scheme 4.

1.35 (m, 2 H), 1.28 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 166.5 (–COO–), 164.5 (–COO–), 132.4, 131.9, 127.7, 111.9, 118.4 (C≡N), 93.2 (C≡C), 85.0 (C≡C), 76.8, 61.5, 42.5, 36.8, 25.1, 22.5, 14.1 ppm. IR (KBr): $\tilde{\nu}$ = 2200, 1730 cm$^{-1}$. MS (EI): *m*/*z* (%): 339 (100) [M]$^+$, 208 (10).

**Ethyl 1-Ethyl-1-methyl-3-[4-(methylsulfonyl)phenyl]prop-2-ynyl Malonate (1f):** 0.735 g, 67% yield; oil. $^1$H NMR: $\delta$ = 7.89 (d, $J$ = 8.5 Hz, 2 H), 7.62 (d, $J$ = 8.5 Hz, 2 H), 4.21 (q, $J$ = 7.1 Hz, 2 H), 3.39 (s, 2 H), 3.06 (s, 3 H), 2.15–1.95 (m, 2 H), 1.78 (s, 3 H), 1.28 (t, $J$ = 7.1 Hz, 3 H), 1.07 (t, $J$ = 7.4 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 166.2 (–COO–), 164.4 (–COO–), 139.7, 132.2, 128.0, 127.0, 92.4 (C≡C), 83.6 (C≡C), 76.7, 61.1, 44.0, 42.1, 34.1, 25.4, 13.8, 8.2 ppm. IR (neat): $\tilde{\nu}$ = 2200, 1730 cm$^{-1}$. MS (EI): *m*/*z* (%): 366 (44) [M]$^+$, 265 (100).

**Ethyl 1-Ethyl-1-methyl-3-pyridin-3-ylprop-2-ynyl Malonate (1g):** 0.528 g, 61% yield, oil. $^1$H NMR: δ = 8.66 (s, 1 H), 8.52 (d, $J$ = 3.6 Hz, 1 H), 7.73 (d, $J$ = 7.9 Hz, 1 H), 7.27–7.20 (m, 1 H), 4.21 (q, $J$ = 7.1 Hz, 2 H), 3.38 (s, 2 H), 2.15–1.85 (m, 2 H), 1.78 (s, 3 H), 1.28 (t, $J$ = 7.1 Hz, 3 H), 1.09 (t, $J$ = 7.5 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 166.5 (–COO–), 164.7 (–COO–), 152.4, 148.8, 138.8, 122.9, 119.8, 92.1 (C≡C), 83.3 (C≡C), 77.3, 61.4, 42.5, 34.5, 25.8, 14.1, 8.5 ppm. IR (neat): $\tilde{\nu}$ = 2200, 1740 cm$^{-1}$. MS (EI): *m*/*z* (%): 289 (73) [M]$^+$, 160 (100).

**3-(4-Chlorophenyl)-1-ethyl-1-methylprop-2-ynyl Ethyl Malonate (1h):** 0.396 g, 72% yield, oil. $^1$H NMR: $\delta$ = 7.36 (d, $J$ = 8.6 Hz, 2 H), 7.26 (d, $J$ = 8.6 Hz, 2 H), 4.20 (q, $J$ = 7.1 Hz, 2 H), 3.36 (s, 2 H), 2.05–1.94 (m, 2 H), 1.76 (s, 3 H), 1.27 (t, $J$ = 7.1 Hz, 3 H), 1.08 (t, $J$ = 7.3 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 166.5 (–COO–), 164.7 (–COO–), 134.5, 133.1, 128.5, 121.2, 89.7 (C≡C), 84.5 (C≡C), 77.5, 61.4, 42.5, 34.5, 25.9, 14.1, 8.6 ppm. IR (neat): $\tilde{\nu}$ = 1740 cm$^{-1}$. MS (EI): *m*/*z* (%): 324 (24) [M + 2]$^+$, 322 (76) [M]$^+$, 191 (100).

**Compound 1i:** 1.071 g, 64% yield, m.p. 86–87 °C. $^1$H NMR: δ = 7.96 (d, $J$ = 8.3 Hz, 2 H), 7.51 (d, $J$ = 8.3 Hz, 2 H), 7.18 (d, $J$ = 8.6 Hz, 1 H), 6.71–6.59 (m, 2 H), 4.19 (q, $J$ = 7.1 Hz, 2 H), 3.87 (s, 3 H), 3.73 (s, 3 H), 3.39 (s, 2 H), 2.90–2.80 (m, 2 H), 2.50–1.40 (m, 13 H), 1.26 (t, $J$ = 7.1 Hz, 3 H), 0.96 (s, 3 H) ppm. $^{13}$C NMR: $\delta$ = 166.4 (–COO–), 166.3 (–COO–), 164.8 (–COO–), 157.6, 137.7, 132.1, 131.7, 129.7, 129.4, 127.5, 126.3, 113.8, 111.5, 91.6 (C≡C), 86.5, (C≡C), 86.1, 61.3, 55.0, 52.1, 48.6, 48.5, 43.5, 42.0, 39.2, 37.3, 33.6, 29.7, 27.4, 26.4, 23.4, 14.1, 13.5. IR (KBr): $\tilde{\nu}$ = 2200, 1750, 1730 cm$^{-1}$.

**Typical Experimental Procedure for the Cyclization of Alkynes 1–3:** Electrolyses were carried out under galvanostatic control ($J$ = 20 mA·cm$^{-2}$) in a divided glass cell (Pt disc gauze cathode, apparent area 2.5 cm$^2$, volume of the catholite: 20 mL) with use of a AMEL 555b potentiostat-galvanostat fitted with an AMEL 731 integrator and an AMEL 868 recorder. The anodic compartment was filled with DMF/TEAP (0.1 M). The counter electrode was a cylindrical platinum gauze. The anodic and cathodic compartments are divided by a glass frit and an agar gel (i.e., methyl cellulose 0.5% volume in DMF/TEAP 0.1 M). The electrolyses were carried out at 0 °C under Ar with $CH_3CN$/TEATFB solutions (0.1 M, 20 mL). After consumption of 2.0 Faradays per mol of alkyne the electrolysis was stopped and the catholyte was transferred into a 50 mL round-bottomed flask containing the alkynes **1**–**3** (0.5 mmol). The resulting solution was stirred under argon at the temperature and for the time stated in Table 2–Table 3. The solvent was then evaporated at reduced pressure and the residue was purified by flash chromatography on silica gel, with elution with hexanes/EtOAc mixtures.

**Ethyl 4-(4-Acetylbenzyl)-5,5-dimethyl-2-oxo-2,5-dihydrofuran-3-carboxylate (4a):** 0.149 g, 94% yield, oil. $^1$H NMR: $\delta$ = 7.84 (d, $J$ = 8.2 Hz, 2 H), 7.26 (d, $J$ = 8.2 Hz, 2 H), 4.25 (q, $J$ = 7.1 Hz, 2 H), 4.09 (s, 2 H, Ar$CH_2$), 2.52 (s, 3 H, $CH_3$CO), 1.29 (s, 6 H), 1.24 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 197.4 (C=O), 178.1, 166.8 (–COO–), 161.5 (–COO–), 140.4, 136.2, 128.9, 128.8, 120.8, 85.9, 61.7, 32.9, 26.6, 25.3, 14.0 ppm. IR (neat): $\tilde{\nu}$ = 1780, 1720, 1680 cm$^{-1}$. MS (EI): *m*/*z* (%): 316 (47) [M]$^+$, 191 (100).

**Ethyl 4-[4-(Ethoxycarbonyl)benzyl]-5,5-dimethyl-2-oxo-2,5-dihydrofuran-3-carboxylate (4b):** 0.142 g, 82% yield, m.p. 114–115 °C. $^1$H NMR: $\delta$ = 7.88 (d, $J$ = 8.3 Hz, 2 H), 7.19 (d, $J$ = 8.3 Hz, 2 H), 4.31–4.15 (m, 4 H, two overlapping $CH_2CH_3$), 4.04 (s, 2 H, Ar$CH_2$), 1.31–1.16 (m, 6 H, two overlapping $CH_2CH_3$), 1.24 (s, 6 H) ppm. $^{13}$C NMR: $\delta$ = 178.0, 166.7 (–COO–), 166.0 (–COO–), 161.5 (–COO–), 140.1, 130.1, 129.6, 128.5, 120.8, 85.9, 61.2, 61.0, 32.9, 25.2, 14.2 ppm. IR (KBr): $\tilde{\nu}$ = 1790, 1710 cm$^{-1}$. MS (EI): *m*/*z* (%): 346 (33) [M]$^+$, 228 (50), 210 (100).

**Ethyl 2-Oxo-4-[3-(trifluoromethyl)benzyl]-1-oxaspiro[4.5]dec-3-ene-3-carboxylate (4c):** 0.178 g, 93% yield, m.p. 101–102 °C. $^1$H NMR: $\delta$ = 7.88 (m, 4 H), 4.20 (q, $J$ = 7.1 Hz, 2 H), 4.05 (s, 2 H, ArC$H_2$), 1.72–1.38 (m, 10 H), 1.19 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 177.7, 167.1 (–COO–), 161.6 (–COO–), 136.2, 131.9, 131.2 (q, $J$ = 32.5 Hz, $C$CF$_3$), 129.3, 125.3 (q, $J$ = 3.6 Hz), 124.0 (q, $J$ = 3.6 Hz), 121.2, 123.5 (q, $J$ = 272 Hz, CF$_3$), 87.8, 61.6, 33.9, 32.7, 24.3, 21.6, 13.9 ppm. IR (KBr): $\tilde{\nu}$ = 1780, 1710 cm$^{-1}$. MS (EI): $m/z$ (%): 382 (28) [M]$^+$, 336 (100), 318 (52).

**Ethyl 4-(4-Cyanobenzyl)-2-oxo-1-oxaspiro[4.5]dec-3-ene-3-carboxylate (4d):** 0.156 g, 92% yield, m.p. 110–112 °C. $^1$H NMR: $\delta$ = 7.55 (d, $J$ = 8.3 Hz, 2 H), 7.27 (d, $J$ = 8.3 Hz, 2 H), 4.21 (q, $J$ = 7.1 Hz, 2 H), 4.08 (s, 2 H, ArC$H_2$), 1.85–1.31 (m, 10 H), 1.20 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 177.3, 166.8 (–COO–), 161.4 (–COO–), 140.7, 132.5, 129.3, 120.8, 111.2, 118.3 (C≡N), 87.7, 61.6, 33.8, 32.9, 24.2, 21.5, 13.9 ppm. IR (KBr): $\tilde{\nu}$ = 2220, 1780, 1720 cm$^{-1}$. MS (EI): $m/z$ (%): 339 (100) [M]$^+$, 293 (47).

**Ethyl 4-(2-Fluorobenzyl)-2-oxo-1-oxaspiro[4.5]dec-3-ene-3-carboxylate (4e):** 0.146 g, 88% yield, m.p. 100–101 °C. $^1$H NMR: δ = 7.19–6.94 (m, 4 H), 4.12 (q, $J$ = 7.1 Hz, 2 H), 4.00 (s, 2 H, ArCH$_2$), 1.70–1.25 (m, 10 H) 1.19 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR: δ = 177.8, 167.3 (–COO–), 161.6 (–COO–), 160.4 (d, $J$ = 246 Hz, C–F), 130.1, 129.0, 124.3, 122.2 (d, $J$ = 15.5 Hz), 120.9, 115.5 (d, $J$ = 21.7 Hz), 87.9, 61.5, 33.5, 25.3, 24.2, 21.6, 13.9 ppm. IR (KBr): $\tilde{\nu}$ = 2220, 1770, 1720 cm$^{-1}$. MS (EI): $m/z$ (%): 332 (30) [M]$^+$, 286 (27), 268 (100).

**Ethyl 5-Ethyl-5-methyl-4-[4-(methylsulfonyl)benzyl]-2-oxo-2,5-dihydrofuran-3-carboxylate (4f):** 0.168 g, 92% yield, m.p. 129–130 °C. $^1$H NMR: $\delta$ = 7.91 (d, $J$ = 8.2 Hz, 2 H), 7.50 (d, $J$ = 8.2 Hz, 2 H), 4.37–4.27 (m, 3 H, one ArCH$_2$ overlapping with OC$H_2$CH$_3$), 4.01 (d, $J$ = 14.6 Hz, 1 H, one ArCH$_2$), 3.07 (s, 3 H), 1.90–1.75 (m, 1 H, one C$H_2$CH$_3$), 1.70–1.55 (m, 1 H, one C$H_2$CH$_3$), 1.35–1.28 (m, 6 H), 0.75 (t, $J$ = 7.3 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 176.5, 166.8 (–COO–), 161.4 (–COO–), 141.4, 139.9, 129.8, 127.9, 122.2, 88.4, 61.7, 44.5, 32.8, 30.7, 23.9, 14.1, 7.4 ppm. IR (KBr): $\tilde{\nu}$ = 1760, 1710 cm$^{-1}$. MS (EI): $m/z$ (%): 366 (4) [M]$^+$, 364 (100).

**Ethyl 5-Ethyl-5-methyl-2-oxo-4-(pyridin-3-ylmethyl)-2,5-dihydrofuran-3-carboxylate (4g):** 0.097 g, 67% yield, oil. $^1$H NMR: $\delta$ = 8.54 (s, 2 H), 7.65–7.60 (m, 1 H), 7.30–7.26 (m, 1 H), 4.33 (q, $J$ = 7.1 Hz, 2 H), 4.20 (d, $J$ = 14.4 Hz, 1 H, one ArCH$_2$), 3.93 (d, $J$ = 14.4 Hz, 1 H, one ArCH$_2$), 1.90–1.81 (m, 1 H, one C$H_2$CH$_3$), 1.69–1.60 (m, 1 H, one C$H_2$CH$_3$), 1.37–1.28 (m, 6 H), 0.74 (t, $J$ = 7.3 Hz, 3 H) ppm. $^{13}$C NMR: $\delta$ = 177.1, 167.0 (–COO–), 161.5 (–COO–), 149.9, 148.8, 136.3, 130.9, 123.7, 121.8, 88.4, 61.8, 30.8, 30.3, 24.0, 14.1, 7.3 ppm. IR (neat): $\tilde{\nu}$ = 1760 cm$^{-1}$. MS (EI): $m/z$ (%): 289 (100) [M]$^+$.

**Ethyl 4-(4-Chlorobenzyl)-5-ethyl-5-methyl-2-oxo-2,5-dihydrofuran-3-carboxylate (4h):** 0.136 g, 84% yield, m.p. 118–120 °C. $^1$H NMR: $\delta$ = 7.22 (d, $J$ = 8.5 Hz, 2 H), 7.13 (d, $J$ = 8.5 Hz, 2 H), 4.27 (q, $J$ = 7.1 Hz, 2 H), 4.12 (d, $J$ = 14.3 Hz, 1 H, one ArCH$_2$), 3.81 (d, $J$ = 14.3 Hz, 1 H, one ArCH$_2$), 1.84–1.70 (m, 1 H, one C$H_2$CH$_3$), 1.65–1.50 (m, 1 H, one C$H_2$CH$_3$), 1.35–1.28 (m, 6 H), 0.67 (t, $J$ = 7.3 Hz, 3 H) ppm. $^{13}$C NMR: δ = 177.3, 167.1 (–COO–), 161.5 (–COO–), 133.2, 133.1, 130.1, 128.9, 121.5, 88.3, 61.6, 32.3, 30.6, 23.9, 14.0, 7.2 ppm. IR (KBr): $\tilde{\nu}$ = 1770, 1720 cm$^{-1}$. MS (EI): $m/z$ (%): 324 (7) [M$^+$ + 2], 322 (19) [M]$^+$, 260 (18), 258 (53), 247 (100).

**Compound 4i:** 0.176 g, 63% yield, m.p. 110–111 °C. $^1$H NMR: $\delta$ = 7.14 (d, $J$ = 8.6 Hz, 1 H), 6.70–6.61 (m, 2 H), 4.29 (q, $J$ = 7.1 Hz, 2 H), 4.11 (d, $J$ = 16.7 Hz, 1 H, one ArCH$_2$), 3.74 (d, $J$ = 16.7 Hz, 1 H, one ArCH$_2$), 3.76 (s, 3 H), 3.74 (s, 3 H), 2.88–2.84 (m, 2 H), 2.30–1.40 (m, 13 H), 1.35 (t, $J$ = 7.1 Hz, 3 H), 1.09 (s, 3 H) ppm. $^{13}$C NMR: $\delta$ = 175.4, 167.0 (–COO–), 166.5 (–COO–), 161.8 (–COO–), 157.7, 140.7, 137.6, 131.5, 130.2, 129.4, 128.9, 126.2, 122.6, 113.9, 111.7, 98.7, 61.7, 55.2, 52.1, 51.2, 50.1, 43.6, 39.1, 35.6, 31.0, 29.7, 29.3, 27.7, 25.9, 23.9, 16.8, 14.0 ppm. IR (KBr): $\tilde{\nu}$ = 1770, 1730, 1700 cm$^{-1}$.

**Compound 4j:** 0.232 g, 96% yield, m.p. 119–120 °C. $^1$H NMR: $\delta$ = 7.14 (d, $J$ = 8.6 Hz, 1 H), 6.70–6.61 (m, 2 H), 4.29 (q, $J$ = 7.1 Hz, 2 H), 4.11 (d, $J$ = 16.7 Hz, 1 H, one ArCH$_2$), 3.74 (d, $J$ = 16.7 Hz, 1 H, one ArCH$_2$), 3.76 (s, 3 H), 3.74 (s, 3 H), 2.88–2.84 (m, 2 H), 2.30–1.40 (m, 13 H), 1.35 (t, $J$ = 7.1 Hz, 3 H), 1.09 (s, 3 H) ppm. $^{13}$C NMR: $\delta$ = 172.4, 167.9 (–COO–), 166.8 (–COO–), 161.4 (–COO–), 157.6, 137.6, 131.5, 126.2, 121.8, 113.8, 111.6, 98.1, 61.5, 55.1, 52.7, 52.3, 50.7, 43.6, 39.0, 35.1, 33.0, 31.3, 29.6, 27.6, 25.9, 24.3, 19.7, 14.1 ppm. IR (KBr): $\tilde{\nu}$ = 1780, 1710 cm$^{-1}$.

**Ethyl 2-Oxo-4-[4-(trifluoromethyl)benzyl]-1,2-dihydroquinoline-3-carboxylate (6a):** 0.128 g, 68% yield, m.p. 144–145 °C. $^1$H NMR: $\delta$ = 11.22 (br s, 1 H), 7.62–7.55 (m, 2 H), 7.52–7.39 (m, 5 H), 7.20–7.10 (m, 1 H), 4.43 (q, $J$ = 7.1 Hz, 2 H), 4.32 (s, 2 H, ArC$H_2$), 1.21 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR ([D$_6$]DMSO): $\delta$ = 166.3, 161.2 (C=O), 146.5, 138.6, 138.5, 131.8, 131.5, 131.2 (q, $J$ = 32.2 Hz, $C$CF$_3$), 129.3, 127.9, 125.6, 125.2 (q, $J$ = 3.6 Hz), 123.8 (q, $J$ = 3.6 Hz), 123.2, 118.6, 117.2, (Ar + C=C), 124.0 (q, $J$ = 272 Hz, CF$_3$), 61.9, 35.9, 14.1 ppm. IR (KBr): $\tilde{\nu}$ = 1730, 1640 cm$^{-1}$. MS (EI): $m/z$ (%): 375 (94) [M]$^+$, 330 (100).

**Ethyl 4-(4-Acetylbenzyl)-2-oxo-1,2-dihydroquinoline-3-carboxylate (6b):** 0.108 g, 62% yield, m.p. 125–126 °C. $^1$H NMR ([D$_6$]DMSO): $\delta$ = 12.25 (br s, 1 H), 7.88 (d, $J$ = 8.2 Hz, 2 H), 7.66 (d, $J$ = 7.4 Hz, 1 H), 7.55–7.47 (m, 1 H), 7.43 (d, $J$ = 8.2 Hz, 2 H), 7.39 (d, $J$ = 7.9 Hz, 1 H), 7.18–7.08 (m, 1 H), 4.29 (q, $J$ = 7.1 Hz, 2 H), 4.27 (s, 2 H, ArC$H_2$), 1.21 (t, $J$ = 7.1 Hz, 3 H) ppm. $^{13}$C NMR ([D$_6$]-DMSO): $\delta$ = 197.2, 165.9, 158.5 (C=O), 145.0, 143.2, 138.6, 135.1, 131.1, 128.4, 128.3, 127.9, 125.9, 122.1, 117.4, 115.8 (Ar + C=C), 61.1, 34.9, 26.5, 13.8 ppm. IR (KBr): $\tilde{\nu}$ = 1740, 1650 cm$^{-1}$. MS (EI): $m/z$ (%): 349 (56) [M]$^+$, 288 (55), 261 (100).

## Acknowledgments

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