# Convenient Synthesis of Cyclic α-Alkoxyl-α,β-unsaturated Carboxylic Acids by Nickel-catalyzed Electrochemical Carboxylation of Lactone Enol Triflates

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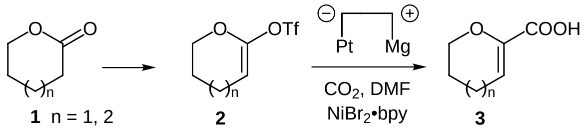
**Abstract:** Electrochemical carboxylation of lactone enol triflates in DMF containing a catalytic amount of $NiBr_2$·bpy with a platinum cathode and a magnesium anode under an atmospheric pressure of $CO_2$ gave the corresponding cyclic α-alkoxyl-α,β-unsaturated carboxylic acids, captodative cycloalkenes, in good yields.

**Key words:** electrochemical carboxylation, carbon dioxide, vinyl triflate, α,β-unsaturated carboxylic acid, captodative alkene

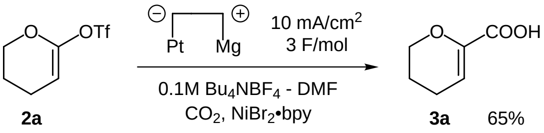


**Scheme 1**

Electrochemical fixation of carbon dioxide is a useful and attractive method for efficient synthesis of various carboxylic acids. We previously reported that electrochemical carboxylation of allylic halides,[1] propargylic bromides,[2] 1,4-dibromo-2-bromomethylbut-2-ene,[3] vinyl bromides,[4] and phenyl-substituted alkenes[5] proceeded efficiently to give the corresponding carboxylic acids in high yields when a magnesium metal was used as a reactive-metal anode.[6] We also reported chemoselective and divergent electrochemical carboxylation of vinyl triflates to give aliphatic β-keto carboxylic acids or phenyl-substituted α,β-unsaturated carboxylic acids.[7] As an extension of our studies on electrochemical fixation of carbon dioxide to organic molecules, we recently found that a nickel-catalyzed electrochemical carboxylation of lactone enol triflates gave cyclic α-alkoxyl-α,β-unsaturated carboxylic acids, captodative cycloalkenes, in good yields.

Although esters of dihydropyrancarboxylic acids **3** (n = 1) could be prepared by a hetero Diels–Alder reaction,[8–10] the synthesis of seven-membered analogs of **3** (n = 2) is not possible using this method. It has also been reported that an intramolecular Wadsworth–Emmons reaction of α-(ω-oxoalkoxyl)phosphonoacetates gave esters of carboxylic acids **3** in moderate yields.[11] In this method, however, troublesome preparation of starting substrates is required. It has also been reported that 3,4-dihydro-2*H*-pyran-6-carboxylic acid (**3**: n = 1) was obtained by hydrolysis of 3,4-dihydro-2*H*-pyran-6-carbonitrile, which was prepared from 3,4-dihydro-2*H*-pyran by dibromination and cyanation followed by dehydrobromination.[9] In this case, preparation of starting cyclic vinyl ethers carrying various substituents, especially seven-membered ones, was not easy. On the other hand, lactone enol triflates are readily prepared from the corresponding lactones.[12–15] The present synthesis of carboxylic acids **3** using electrochemical carboxylation could be achieved from these readily available lactones in only two steps. There have been no reports on electrochemical carboxylation of lactone enol triflates giving cyclic α-alkoxyl-α,β-unsaturated carboxylic acids **3**, although direct[7] and palladium-catalyzed[16] electrochemical carboxylations of vinyl triflates have been reported. In this communication, we report a convenient method for synthesizing cyclic α-alkoxyl-α,β-unsaturated carboxylic acids **3** by nickel-catalyzed electrochemical carboxylation of lactone enol triflates **2**.

Lactone enol triflates **2** were prepared from the corresponding lactones by a modification of the previously reported procedure.[12,17] Reaction of appropriate lactones with LDA in THF at –78 °C followed by the addition of 2-bis(trifluoromethanesulfonyl)aminopyridine[17] gave the corresponding lactone enol triflates **2** in moderate to good yields (Scheme 1). As the first attempt, direct electrochemical carboxylation of lactone enol triflate **2a** was carried out according to our previously reported electrochemical method.[7] However, a complex mixture of carboxylic acids was only obtained in a very low yield, and the starting triflate **2a** was recovered in about 60% yield. Thus, we next attempted electrochemical carboxylation of lactone enol triflates **2a** in the presence of $NiBr_2$·bpy, which has been shown to be effective for electrochemical carboxylation of alkyl-substituted vinyl bromides.[4b] Electrochemical carboxylation of **2a** in the presence of 20 mol% of $NiBr_2$·bpy gave an expected cyclic α-alkoxyl-α,β-unsatureted carboxylic acid **3a** in 65% yield (Scheme 2).



**Scheme 2**

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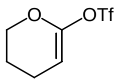
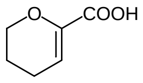
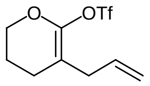
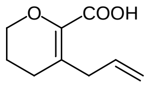
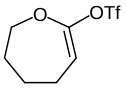
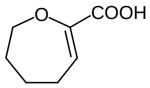
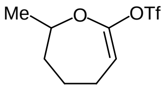
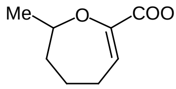
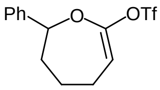
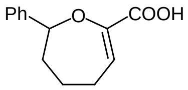
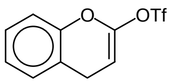
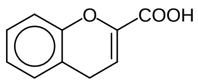
The results of the present electrochemical carboxylation of lactone enol triflates **2** are summarized in the Table. Similar electrochemical carboxylation of seven-membered enol triflates **2c**–**e** also gave the corresponding carboxylic acids **3c**–**e** in 71–79% yields (entries 3–5). This method was also applicable to the synthesis of bicyclic products. Thus, triflate **2f**, readily prepared from 3,4-dihydrocoumarine, was subjected to this electrochemical carboxylation to give the corresponding 4*H*-chromene-2-carboxylic acid (**3f**) in 71% yield (entry 6). In all cases, a small amount of diene, which was derived from the nickel-catalyzed dimerization of triflates **2**, was detected by $^1$H NMR.

A typical procedure for the nickel-catalyzed electrochemical carboxylation is as follows. Lactone enol triflate **2a** (700 mg, 3.0 mmol), which was readily prepared from δ-valerolactone in 79% yield, in 15 mL of DMF containing 0.1 M $Bu_4NBF_4$ was electrolyzed in the presence of 20 mol% of $NiBr_2$·bpy at 5 °C at a constant current (current density: 10 mA/cm$^2$) under an atmospheric pressure of carbon dioxide. A one-compartment cell equipped with a platinum plate cathode (2 × 3 cm$^2$) and a magnesium rod anode (3 mmϕ) was used for electrolysis. The electricity passed was 3 F/mol. After electrolysis, the electrolyzed solution was acidified with 1 N HCl and extracted with diethyl ether. The ethereal solution was washed successively with $H_2O$ and saturated $NaHCO_3$. The aqueous solution was again acidified carefully with 6 N HCl, and the resulting carboxylic acid was extracted with diethyl ether. The combined ethereal solutions were washed with saturated brine and dried over $MgSO_4$. Evaporation of the solvent gave an almost pure 3,4-dihydro-2*H*-pyran-6-carboxylic acid (**3a**) (250 mg, 65%).

Cyclic voltammetry of lactone enol triflate **2a** and $NiBr_2$·bpy was carried out. No reduction peak of **2a** was observed at > –3.1 V *vs* Ag/Ag$^+$ and a reduction peak of $NiBr_2$·bpy appeared at –1.25 V *vs* Ag/Ag$^+$.[4b] On the other

**Table** Nickel-catalyzed Electrochemical Carboxylation of Lactone Enol Triflates **2**[a]

| Entry | Triflate | Product and Yield[b] |
|---|---|---|
| 1 | <br>**2a** | <br>**3a** 65% |
| 2 | <br>**2b** | <br>**3b** 63% |
| 3 | <br>**2c** | <br>**3c** 74% |
| 4 | <br>**2d** | <br>**3d** 79% |
| 5 | <br>**2e** | <br>**3e** 71% |
| 6 | <br>**2f** | <br>**3f** 71% |

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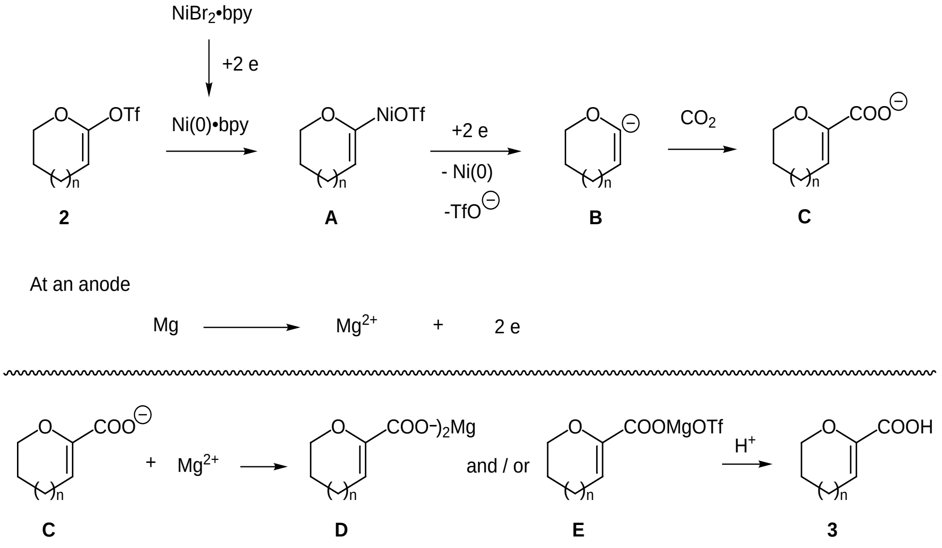
[a] Lactone enol triflate **2** (3 mmol) in DMF containing 0.1 M $Bu_4NBF_4$ was electrolyzed in the presence of 20 mol% of $NiBr_2$·bpy at 5 °C with a constant current (10mA/cm$^2$) under $CO_2$. A one-compartment cell equipped with a platinum plate cathode (2 × 3 cm$^2$) and a magnesium rod anode (3 mmϕ) was used. The electricity passed was 3 F/mol.

[b] Isolated yields.



**Scheme 3**

hand, cyclic voltammetry of **2a** in the presence of $NiBr_2$·bpy showed the existence of a new reduction peak at –1.75 V *vs* Ag/$Ag^+$ and showed that the reduction current of this peak increased when the amount of $NiBr_2$·bpy increased. From these results we propose the following reaction pathways, as shown in Scheme 3. At a cathode, a two-electron reduction of $NiBr_2$·bpy occurs to give Ni(0)·bpy. Oxidative addition of an Ni(0) catalyst to vinyl triflates **2** gives nickel(II) complex **A**. A two-electron reduction of complex **A** at a cathode generates a vinyl anion **B**, which reacts with $CO_2$ to give the corresponding carboxylate ions **C**. On the other hand, at an anode, dissolution of magnesium metal occurs to give magnesium ions. The magnesium ions readily capture carboxylate ions **C** to form stable magnesium carboxylates **D** or **E**, which upon acid treatment gives carboxylic acid **3**.

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