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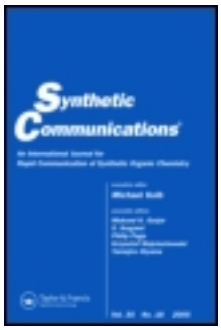

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# Versatile Methodology to Hydrate Alkynes, in the Presence of a Wide Variety of Functional Groups, with Mercury(II) p-Toluensulfonamidate, Under Catalytic, Mild and Neutral Conditions

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# VERSATILE METHODOLOGY TO HYDRATE ALKYNES, IN THE PRESENCE OF A WIDE VARIETY OF FUNCTIONAL GROUPS, WITH MERCURY(II) *p*-TOLUENSULFONAMIDATE, UNDER CATALYTIC, MILD AND NEUTRAL CONDITIONS

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**Abstract**

A method to generate carbonylic compounds from alkynes under mild and neutral conditions, with excellent functional group compatibility and high yields, is described. Hydration takes place under catalytic conditions by using from 0.1 to 0.2 equivalents of the easily available and inexpensive mercury(II) *p*-toluensulfonamidate in a hydroalcoholic solution. After use the catalyst is inertized and/or recycled.

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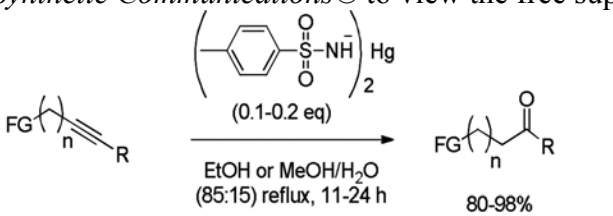


**FG**: -$N_3$, -Cl, -CN, -OH, -COOMe
-COMe, -Cyclic ketone
-OMe, -OEt, -OBn, Cyclic ether
-$CH(OMe)_2$, -OMEM,
-H, -Alkyl, -Alkenyl, -Alkynyl, -Aryl

**R**: H, Alkyl, Ph, Alkynyl

**KEYWORDS:** Acetylene / Carbonylic compounds / Catalyst / Hydration / Mercury(II) *p*-Toluensulfonamidate / Regioselectivity / Stereoselectivity

## 1. INTRODUCTION

The addition of water to alkynes to obtain carbonyl compounds is a very useful reaction in organic chemistry.[1] The traditional methods based on mercury(II) catalysts[2] hydrate

internal and terminal alkynes to give the Markovnikov adduct. Usually and acid is required to form the carbonyl product in this typical methods. The use of an acid considerably reduces the functional group compatibility and narrows the scope of the methodology. When using a buffered system like mercury(II) triflate-TMU complex[3] a good functional group compatibility is observed, except for substrates containing acetal or benzyl groups.[4]



Other methods have been reported that use catalysts based on gold(I),[5] gold(III),[6] platinum(II),[7] palladium(II),[8] rhodium (III)[9] and ruthenium(II)[10]to form the anti-Markovnikov product. These are very efficient catalyst but the main disadvantage of these methods is the cost of the catalysts based on noble metals.

The present full paper reports a catalytic method under neutral conditions based on the inexpensive reagent mercury(II) *p*-toluensulfonamidate.[11]The efficiency of this reagent in the hydration of terminal alkynes has been proven by us, under stoichiometric conditions, for the total synthesis of 1,7-epoxycyclononanes[12]affording intermediate diketones in excellent yields (Table 1). Under these reaction conditions polymerization and epimerization of the substrates (especially at the alpha position of ketones) were avoided due the neutral and mild conditions used.

Herein we report that mercury(II) *p*-toluensulfonamidate is a highly effective and inexpensive[13] catalyst with an excellent functional group tolerance for the hydration of terminal and internal alkynes, even with acetal or benzyl substrates. Furthermore we

report the chemoselective hydration of the most accessible alkyne group in some dialkyne substrates. On the other hand, the use of tiny catalytic amounts of this catalyst, together with its inertization and/or recovery, avoids possible toxic and /or environmental impacts.

## 2. RESULTS AND DISCUSSION

In our initial assays we worked under stoichiometric conditions of $Hg(TsNH)_2$ with the 8-oxabicyclo[3.2.1]octane substrates(Table 1). The main characteristic of thesesubstrates is the presence of a protected propargylic alcohol group and one stereocenter in *α* to the carbonyl group (on C-3), sensitive to epimerization.

Upon treatment of **1** with 1.3 eq. of mercury(II) sulfonamidate in a (85:15) mixture of ethanol:water as a solvent for 24 h, the dicarbonyl product **2** was obtained in quantitative yield. It is important to note that the benzyl group (Table 1, entry 1) does not cleave at all upon the hydration reaction. Also the acetalic group methoxymethyl remains stable (Table 1, entry 4). Thus, the sensitive substrate **7** that contains the acetalic protecting group methoxymethyl (OMEM) was converted into **8** in quantitative yield.

The methoxy and ethoxy substrates **3** and **5** also afforded the hydration products **4** and **6** with high yields. Finally, the hydration reaction of **9** also gave the carbonylic product **10** with high yield.

In all these reactions the epimerization product at the α carbons of both ketone groups, in the final product, was not observed. However this problem was detected previously by us

working with other hydration methods that need the use of an acid (i.e $HgSO_4/H_2SO_4$). Moreover, by working with $Hg(TsNH)_2$ under neutral conditionsthe R group at the propargylic position was not cleaved at all.

The next step in our project was to investigate how the reaction took place under catalytic conditions and the functional group compatibility (Table 2). Phenylacetylene**11** reacted under catalytic conditions, using 0.1 eq of $Hg(TsNH)_2$, to form acetophenone**12** in excellent yield, which indicates that the electron delocalization of the triple bond towards the aromatic ring does not interfere in the reaction. Hydration of 1-heptyne **13** to afford 2-heptanone **14** demonstrates that the reaction works with good yield for substrates with alkyl linear chains. A dialkyne substrate **15** was also dihydrated with 0.17 eq. into 2,7-octadienone **16**. Methyl ester **17**,nitrile **19** and chloride **21** groupsdid not interfere with the catalytic cycle and completely converted into the ketone products **18**, **20** and **22**,respectively.

Due to the low solubility of substrates **23** and **27** in methanol, the reactions were carried out in (85:15) ethanol:water as a solvent. The hydration of both products gave **24** and **28** in good yields. The dimethoxyacetal substrate **25** was efficiently converted into product **26**, without observing any degree of hydrolysis of this acid sensitive group, under these mild neutral conditions. Finally, alcohol **29** was converted into the ketone **30** in good yield, and no anchimeric influence of the hydroxyl group was observed on the yield and regioselectivity of the reaction.

Most of substrates (Table 2) were also reacted with mercury(II) *p*-toluensulfonamidate under stoichiometric conditions (1:1.3 eq.), with similar reaction times, conversions and yields. The reaction also converted substrates with internal C≡C bonds into carbonyl compounds (Table **3**). Due to the characteristics of the catalyst, the selective hydration of the terminal alkyne group in front of the internal triple bonds is accomplished, under reflux conditions, on substrates in which one of the C≡C bonds is sterically hindered. This steric-controlled chemoselectivity could have interest in synthetic organic chemistry.



The non-hindered dialkyne substrate **31** was used as a standard substrate and it was hydrated under catalytic conditions, to afford the dicarbonyl products **32** and **33** in a 1:1 ratio. In this case, as expected, no chemoselectivity was observed, and both C≡C bonds were hydrated, but with complete regioselectivity for the terminal C≡C bond. 1,1,3-Triphenylpropargyl alcohol **34** did not react under reflux of solvent even with 1.3 eq. of mercury(II) *p*-toluensulfonamidate, and even for long reaction times, due to the steric hindrance around the C≡C bond. The reaction conditions were forced by using microwave irradiation and then the hydration took place regioselectively, by insertion of the hydroxyl group on the carbon atom $\alpha$ to the aromatic ring. Product **35** was obtained and also the dehydration product **36** as a major product (in a ratio of 1:6), due to **35** is a $\beta$-hydroxyketone that dehydrates to afford the highly conjugated $\alpha,\beta$-unsaturated ketone **36**.

Then, this hydration methodology was studied for substrate **37**, a diacetylene having a terminal -C≡CH bond and a hindered -C≡C-$CR_3$ triple bond. This study was performed under two different reactions conditions: a) Under reflux of solvent only the methyl ketone was obtained and the internal triple bond was not hydrated at all, affording **38** in 80 % yield. No other products were detected by NMR or GC, which demonstrates *achemoselective discrimination*. b) Under microwave conditions substrate **37** was completely converted; a 62% of the substrate was dihydrated and formed the 1,5-dicarbonylic compound **39**, which lost the alcohol group. The reaction also afforded the monohydrated product **38**, in a 36% yield. In this case an unexpected regioselective hydration of the internal alkyne was observed, and a 1,5-dicarbonyl compound was obtained instead of a 1,6-diketone, which is the product expected from the usual hydration mechanism, due to the insertion of the Hg-ligand entity on the less acetylenic carbon (Scheme 2).[14], [15]

The explanation for this result could be based on the fact that the hydration of the terminal alkyne is faster than that of the internal one, thus the product **38** is obtained as a reaction intermediate, then in a second step a 1,5-dicarbonyl compound **39** is formed instead of the 1,6-diketone by the anchimeric assistance of the initially formed carbonyl group, according to a mechanism previously reported[16] (Scheme 2).

The general reaction mechanism proposed (Scheme 3) consists on a catalytic cycle.[17] The first step is the coordination of Hg(II) to the triple bond **(I)** followed by the addition

of water to the carbon that supports better the partial positive charge **(II)**, avoiding interactions of the R group with the Hg-ligand entity.

Then the *β*-hydroxyethynyl-mercury intermediate **(III)** is formed, which after a proton exchange forms the oxonium cation **(IV).** Intermediate **(IV)** could afford the *α*-mercuriated carbonyl compound **(V)** that has been characterized by X-ray diffraction analysis in previous studies.[14]



## 3. CONCLUSIONS

We may conclude that we have developed a catalytic method to hydrate terminal and internal triple bonds under mild and neutral conditions. The hydration reaction with mercury(II) *p*-toluensulfonamidate does not cleave the acid sensitive groups: dimethoxyacetal, benzyl, and propargylicmethoxymethylmethoxy and ethoxy groups. The reaction conditions are compatible with a wide variety of other functional groups as azides, alcohols, nitriles, esters, ketones or terminal double bonds. These neutral conditions also avoid epimerization of enolizable substrates. This catalytic approach and the recovery of the insoluble mercury byproducts by filtration or centrifugation considerably minimize the environmental and safety impacts of the process.

Last but not least, this methodology is also an alternative much more economic[13] than other hydration reactions of C≡C triple bonds. Further efforts are under way in our laboratory to study the reaction under conditions very different from that reported here and using much lower amounts of catalysts.

## 4. EXPERIMENTAL SECTION

### 4.1. General Procedures

NMR-spectra were recorded on a Varian Inova 300 and/or a Mercury 400 apparatus. Chemical shifts (δ) are expressed in ppm versus tetramethylsilane as an internal standard. IR spectra were recorded on a NICOLET 6700 FT-IR by film, KBr pellet or ATR (Attenuated Total Reflectance) methods. Mass spectrometry was performed on a Hewlett-Packard 5890 apparatus, generally under a CI (Chemical Ionization) method by using $NH_3$ or $CH_4$ or by direct insertion under Electron Impact a 70eV and 150 ºC. The elemental analyses were obtained in a FISONS Elemental Analyzer, Model Na-1500. The samples were previously pyrolized at 1000ºC under oxygen atmosphere and the content of carbon and hydrogen was determined by evaluation of the combustion gases by gas chromatography using a FID detector. All solvents were dried according to standard procedures and distilled prior to use. All other major chemicals were obtained from commercial sources and used without further purification. Gas chromatography was perfomed by using a Shimatzu AOC-20i apparatus with a capilary column HP-5 Crosslinked 5%Ph-Me-Siloxane(L =30 m, $\phi_i$ = 0.32 mm, Film Thickness = 0.25 μm) under the following experimental conditions: $T_i$= 35 ºC, $t_i$= 1 min, Rate= 5ºC/min, $T_f$= 250 ºC, $t_f$= 5 min, split 1:100; gas brands and preasures are: He = 5.5 bar (Linde, Helio 5.0), Air= 3 bar (Linde, Aire Sintético), $H_2$= 3 bar (Linde, $H_2$ 5.0).

### 4.2. Preparation Of Catalyst:

#### 4.2.1. Preparation Of *P*-Toluensulfonamide

Commercial tosyl chloride (117.73 g, 0.61 mol) dissolved in acetonitrile (590 mL) was slowly added to a magnetically stirred solution of ammonium hydroxide (197 mL, 3.09 mol) under Ar atmosphere. The reaction mixture was stirred for 30 min. After completion of the reaction, the excess of ammonium hydroxide was neutralized by using concentrated HCl. Then, the solvent was evaporated and a white solid formed. The solid was washed with water (to remove $NH_4Cl$) and dried under vacuum affording pure product as white solid (87.78 g, 83%): **MP:** 137-138 ºC (EtOH). **$^1$H NMR** (300 MHz, $CDCl_3$) δ ppm: 7.82 (d, *J*=8.1 Hz, 2H, H2, H6), 7.32 (d, *J*=8.1 Hz, 2H, H3, H5), 4.72 (br s, 2H, H1'), 2.44 (s, 3H, H7).**$^{13}$C NMR** (100 MHz, $CDCl_3$) δ ppm: 143.71 (C4), 139.03 (C1), 129.70 (C3,C5), 126.44 (C2,C6), 21.51 (C7). **IR** (KBr) ν: 3329 (N-H, st), 3232 (N-H, st), 3017 ($Csp^2$-H, st), 2919 ($Csp^3$-H, st), 1911-1793 (comb), 1588 (N-H, δ), 1322 (S=O, st as), 1015 $cm^{-1}$. **MS** [DIP-EI, 70 eV, 150 ºC, m/z (%)]: 171 ($M^+$, 40), 169 ($M^+$-H, 10), 156 ($M^+$-Me, 16), 155 ($M^+$-$NH_2$, 50), 91 ($M^+$-$SO_2NH_2$, 100), 65 (43). **HRMS**: Calcd. For $C_7H_9NO_2S$ 171.03540. Found: 171.03536.

### 4.2.2. Preparation Of Mercury(II) *P*-Toluensulfonamidate

*p*-Toluensulfonamide (29.66 g, 173.2 mmol) and HgO (18.28 g, 83.1 mmol) were grounded together in a mortar to get a very fine and homogeneous powder. The mixture was placed in a crucible and warmed up to 200ºC in an oven for 1.5 h. The mixture was stirred with a glass bar every 15 min. Once the orange color of HgO disappears the reaction is complete. The crucible was cooled down to room temperature and the solid was transferred to a round-bottomed flask fitted with a reflux condenser. EtOH (150 mL) was added and the solution was refluxed for 30 min. to dissolve unreacted *p*-

toluensulfonamide excess, then, the mixture was filtered when hot. After lixiviation the resulting residue was dried in a desiccator containing phosphorus pentoxide for 1 day to obtain pure productas a white solid (36.12 g, 89%). **MP**: 249.8-250.7 ºC (in closed capillary tube, previously purged with Ar).**IR** (KBr): 3307 (N-H, st), 3036-3024 ($Csp^2$-H, st), 2978 ($Csp^3$-H, st), 1910-1652 (comb), 1276 (S=O, st, as), 1139 (S=O, st, sym), 945 (S-O, st), 812 $cm^{-1}$.**$^1$H NMR** (400 MHz, DMSO-$d_6$) δ ppm: 7.68 (d, *J* = 8.0 Hz, 4H; H2, H6, H2‘, H6‘), 7.34 (d, *J*=8.0 Hz, 4H; H3, H5, H3‘, H5‘), 2.35 (s, 6H, H7 and H7‘).**EA.** Calcd. for $C_{14}H_{16}HgN_2O_4S_2$: C, 31.08; H, 2.98; N, 5.18; S, 11.85 %. Found : C, 31.11; H, 3.01; N, 5.15; S, 11.83 %.



**4.3. Hydration Procedures:**

**4.3.1. Procedure For The Hydration Reaction With Mercury(II) *P*-Toluensulfonamidateunder Stoichiometric Conditions**

To a stirred suspension of mercury(II) *p*-toluensulfonamidate (892 mg, 1.65 mmol) in a mixture of MeOH:$H_2O$ (85:15) (30 mL) under Ar atmosphere, methyl hept-6-ynoate **(17)** (178 mg, 1.27 mmol) was added in the same solvent system (5 mL). The mixture was warmed up to reflux of solvent and stirred for 13 h.

**4.3.2. Procedure For The Hydration Reaction With Mercury(II) *P*-Toluensulfonamidate Under Catalytic Conditions.**

To a stirred solution of mercury(II) *p*-toluensulfonamidate (16.4 mg, 0.03 mmol) in a mixture of MeOH:$H_2O$ (85:15) (20 mL) under Ar atmosphere and warmed up to reflux,

11-chloroundec-1-yne **(21)** (51 mg, 0.28 mmol) was added in the same solvent system (5 mL). The mixture was stirred under reflux of solvent for 20 h.

**4.4. Work-Up Procedures:**

**4.4.1. Usual Work-Up Procedure For Isolation Of Low-Boiling Point Products**

To a stirred solution of mercury(II) *p*-toluensulfonamidate (225 mg, 0.42 mmol) in a mixture of MeOH:$H_2O$ (85:15) (50 mL), 1-heptyne **(13)** (200 mg, 2.08 mmol) was added in the same solvent system (10 mL), under Ar atmosphere, and the mixture was warmed up to reflux of solvent and stirred under these conditions for 14 h. After completion of the reaction (control by TLC, CG), the mixture was cooled down to room temperature and the mercury(II) catalyst precipitated with an aqueous 10% (w/w) solution of $(NH_4)_2S$ (0.6 mL). The precipitate of HgS was removed by centrifugation. Then, the mother liquor was extracted with *n*-pentane (x6), the organic layers were combined together, dried over $MgSO_4$ and filtered. Pentane was removed by slow simple distillation at atmospheric pressure, using a Vigreux column, affording pure product **(14)**(186.2 mg, 78%).

**4.4.2. Usual Work-Up For High-Boiling Products**

To a stirred solution of mercury(II) *p*-toluensulfonamidate (74.4 mg, 0.14 mmol) in a mixture of MeOH:$H_2O$ (85:15) (40 mL) 5-hexynenitrile **(19)** (165 mg, 1.72 mmol) was added in the same solvent system (6 mL), under Ar atmosphere, and the mixture was warmed up to reflux of solvent and stirred under these conditions for 21 h. After completion of the reaction (control by TLC, CG), the crude mixture was cooled down to room temperature and an aqueous 10% (w/w) solution of $(NH_4)_2S$ (0.2 mL) was added.

The resulting mixture was filtered through a short column of silica gel and alumina (1:1) to remove HgS, which at the end is collected and processed properly. The hydro-alcoholic solution was concentrated in order to remove alcohol (MeOH or EtOH) and the resulting residue dissolved in $Et_2O$. The ethereal solution was extracted with NaOH (2 M) (x3). The aqueous layers were combined and extracted again with diethyl ether. The organic layers were combined together, extracted with brine, dried over $MgSO_4$, filtered and concentrated to dryness. The crude product was then submitted to a flash column chromatography on silica gel, eluting with mixtures of hexane and ethyl acetate (or diethyl ether) of increasing polarity, obtaining with H/AcOEt 50:50 pure product **(20)** (178.4 mg, 93.3%).



## 6. SUPPORTING INFORMATION:

Synthetic procedures for theacetylenic substrates and complete spectroscopic characterization of acetylenes and their hydration products are included in the Supplementary Material (S1), available online. In addition, copies of $^{1}H$ NMR, $^{13}C$ NMR and IR spectra of acetylenic substrates and hydration products are included also as Supplementary Material (S2) and are available in the Web page of this journal.

## 5. ACKNOWLEDGMENTS

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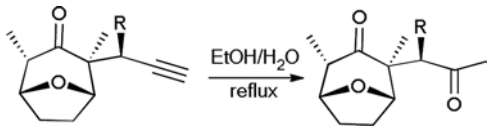
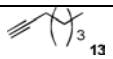
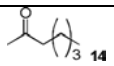
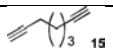
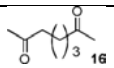
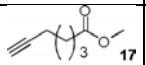
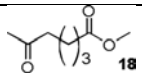
Table 1. Hydration of terminal alkynes of 1,7-epoxycyclononane substrates with $Hg(TsNH)_2$ under stoichiometric conditions (1:1.3 eq.).

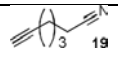
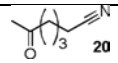
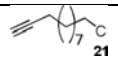
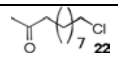
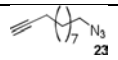
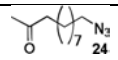
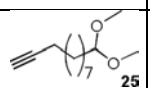
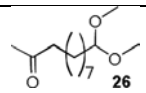
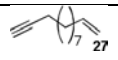
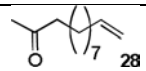
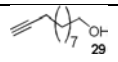
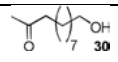



| *Entry* | R group | Substrate | Time (h) | Product | Yield (%)[a], [b], [c] |
|---|---|---|---|---|---|
| 1 | OBn | **1** | 24 | **2** | 92-100 |
| 2 | OMe | **3** | 23 | **4** | 85 |
| 3 | OEt | **5** | 18 | **6** | 85 |
| 4 | OMEM | **7** | 24 | **8** | 98 |
| 5 | H | **9** | 24 | **10** | 85 |

[a] Isolated yields. [b] The reaction yields are quantitative by NMR or GC (using internal standard). [c] Conversion in all cases is 100%.

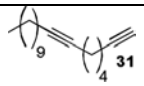
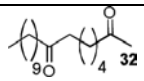
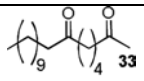
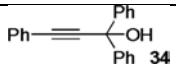
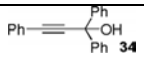
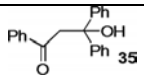
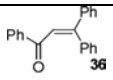
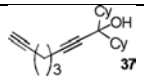
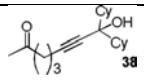
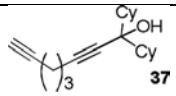
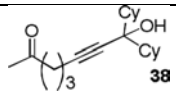
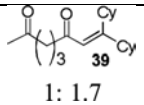
Table 2. Chemoselective hydration of alkynes having different functional groups, by using catalytic amounts of $Hg(TsNH)_2$ .

| Entry | Substrate | Conditions | Product | Eq. $Hg(TsNH)_2$ (mmol/mmol of substrate) | Conversion (%) | Yield (%)[c],[d],[e] | Ref. |
|---|---|---|---|---|---|---|---|
| 1 |  11 | MeOH/$H_2$O Reflux, 20 h |  12 | 0.10 | 100 | 80 [e] | [a] |
| 2 |  13 | MeOH/$H_2$O Reflux, 14 h |  14 | 0.20 | 100 | 78 [e] | [a] |
| 3 |  15 | MeOH/$H_2$O Reflux, 39 h |  16 | 0.17 | 100 | 82 [e] | [a] |
| 4 |  17 | MeOH/$H_2$O Reflux, 22 |  18 | 0.11 | 100 | 98 | [a] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | h | | | | | |
| 5 |  19 | MeOH/$H_2O$ Reflux, 21 h |  20 | 0.08 | 100 | 93 | [a] |
| 6 |  21 | MeOH/$H_2O$ Reflux, 20 h |  22 | 0.11 | 100 | 88 | [b] |
| 7 |  23 | EtOH/$H_2O$ Reflux, 66 h |  24 | 0.10 | 100 | 80 | [b] |
| 8 |  25 | MeOH/$H_2O$ Reflux, 48 h |  26 | 0.21 | 100 | 85 | [b] |
| 9 |  27 | EtOH/$H_2O$ Reflux, 24 h |  28 | 0.20 | 100 | 80 | [b] |
| 10 |  29 | MeOH/$H_2O$ Reflux, 38 h |  30 | 0.20 | 100 | 93 | [b] |

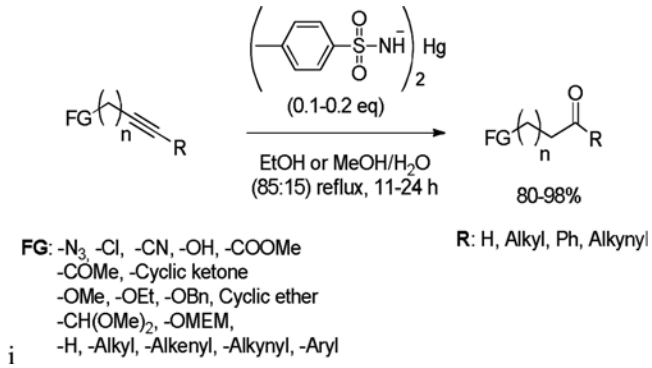
[a] Commercially available substrates. [b] Synthesized substrates. [c] Isolated yields (by column chromatography). [d] The reaction yields are quantitative by NMR and GC (using internal standard). [e] The reactions have been performed several times at different scales (20-300 mg), showing robustness. However, it has been observed a loss of mass in the case of low boiling products during work-up, especially for those products that form azeotropes with the solvents. Alternative isolation procedures for these products are described in the experimental section.

Table 3. Chemoselective hydration catalyzed by $Hg(TsNH)_2$ of dialkynes having two differently hindered C≡C bonds.

| Entry | Substrate | Conditions | Product 1 | Product 2 | Eq. $Hg(TsNH)_2$ | Conversion (%) | Yield (%)[c] | Ref. |
|---|---|---|---|---|---|---|---|---|
| 1 |  31 | $EtOH/H_2O$ Reflux, 16 h |  32 |  33 1:1 1:1 | 0.2 | 100 | 95 | [b] |
| 2 |  34 | $MeOH/H_2O$ Reflux, 24 h | - | - | 1.3 | 0 | - | [a] |
| 3 |  34 | $MeOH/H_2O$, microwave, 130ºC, 8 bar, 27 h |  35 |  36 1:6 1:6 | 0.2 | 96 | 93 | [a] |
| 4 |  37 | $MeOH/H_2O$ Reflux, 24 h |  38 | - | 0.2 | 82 | 80 | [b] |
| 5 |  37 | $MeOH/H_2O$, microwave, 130ºC, 8 bar, 20 h |  38 |  39 1: 1.7 1: 1.7 | 0.2 | 100 | 98 | [b] |

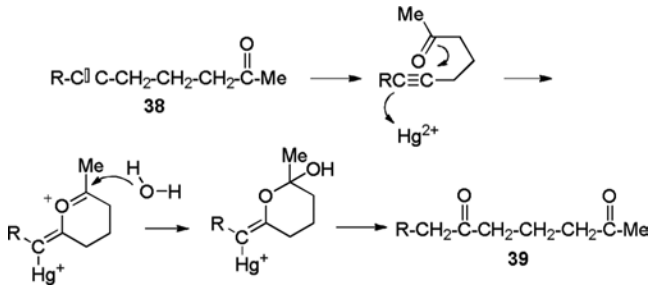
[a] Commercially available substrates. [b] Synthesized substrates. [c] Isolated yields (by column chromatography).

Scheme 1. General overview of the alkyne hydration with mercury(II) *p*-toluensulfonamidate under mild and neutral conditions.




i

Scheme 2. Proposed mechanism for the regioselective formation of 1,5-diketones by anchimeric assistance of the initially formed carbonyl group.



Scheme 3. Proposal of a catalytic cycle for the hydration process.