dations conducted with 6 equiv of manganese(III) acetate in combination with 12 equiv of a carboxylic acid also proved to be a particularly convenient procedure, as summarized in Table II. An examination of these examples revealed that this process was compatible with enones 1 having hydroxyl, ester, ketal, and *tert*-butyldimethylsilyl ether functionality and was also compatible with carboxylic acids having a variety of alkyl substitution patterns or halogen substituents on the α carbon of the carboxylic acid. The process was not compatible with carboxylic acids having benzylic hydrogens (e.g., phenylacetic acid), α-hydroxy (e.g., lactic acid, mandelic acid), or α-methoxy substituents, and the process, in the few cases that were examined, exhibited little asymmetric induction using chiral carboxylic acids (e.g., (*S*)-(+)-2-methylbutyric acid). Despite these limitations, this oxidation accommodated a variety of different enone 1 and carboxylic acid components and the efficient regioselective coupling at the α'-position[12] is noteworthy.

The following general procedure was employed for oxidations using manganese(III) acetate in combination with carboxylic acids. A mixture of 15 mmol of manganese(III) acetate and 30 mmol of carboxylic acid in 50 mL of benzene was refluxed for 45 min under a Dean–Stark trap. The mixture was cooled to 25 °C, and 2.5 mmol of enone[13] 1 was added. The mixture was refluxed until the dark brown color disappeared (6–18 h). The mixture was cooled to 25 °C, diluted with ethyl acetate, washed successively with 1 M hydrochloric acid solution, aqueous saturated sodium bicarbonate solution, and brine, and dried over anhydrous magnesium sulfate. The crude products were chromatographed on silica gel to afford the α'-acyloxy enones 2 having IR, NMR, and mass spectral data in support of the assigned structures. In the case of oxidations using manganese(III) acetate in combination with manganese(II) carboxylates, 15 mmol of the manganese(II) carboxylate was substituted for the 30 mmol of carboxylic acid in the above procedure.

Acknowledgment. We thank the National Institutes of Health (Grant GM-36256) for their generous financial support, the North Atlantic Treaty Organization for a travel grant (No. 0346/88), the University of Kentucky for the purchase of Bond Issue Equipment, and the University of Kentucky Mass Spectrometry Center for exact mass determinations.

Supplementary Material Available: Characterization data for compounds **2a–t** (7 pages). Ordering information is given on any current masthead page.

(12) For an exception to this α'-regioselectivity, see: Ahmad, M. S.; Ahmad, S. Z.; Ansari, I. A. *J. Chem. Res. (S)* **1984**, 374.

(13) All enones were commercially available with the exception of spiro[5.5]undec-1-en-3-one, which was prepared according to: Kane, V. V. *Synth. Commun.* **1976**, *6*, 237.

Reductive Tandem Cyclization of Allyl Pentenyl Ketones

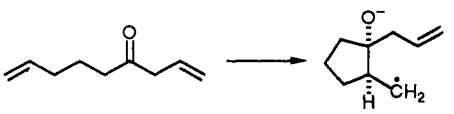
Essie Kariv-Miller,* Hatsuo Maeda, and Franco Lombardo

Department of Chemistry, University of Minnesota, Minneapolis, Minnesota 55455

Received April 10, 1989

Summary: Bicyclo[3.3.0]octanols were synthesized in one step, by cathodic reduction of linear allyl pentenyl ketones.

Sir: Cathodic cyclization[1,2] of 6-hepten-2-ones and related compounds provides a remarkable example of a high yield, highly stereoselective electrochemical process. This selectivity, which is not duplicated by chemical reductions, arises from a delicate balance of kinetic factors which allow stereospecific ketyl addition to an unactivated alkene to succeed in competition with proton and electron transfers, and reversible cyclization which destroys stereochemistry.[2] In this study we set out to expand the synthetic scope of this method, investigating a "tandem" bicyclization process. It was hypothesized that an initial ketyl cyclization would give a substituted 5-hexenyl radical 1, appropriate for a radical cyclization onto the allyl moiety. This hypothesis



1

was attractive for bicyclization because reactants of this type are readily available and because the ketyl cyclization stereochemistry will lead to a cis-ring juncture. The products are interesting because bicyclo[3.3.0]octanol systems of this type are found in a number of natural products.

Although tandem cyclizations are known[3] for certain dienyl halides with tin hydride reagents, they are not known for reduction of dienones. The closest example[4]

Table I. Reduction of 2 at a Hg Pool Cathode (DMF Solvent, 0.1 M Bu_4NBF_4 Supporting Electrolyte)[a]

conditions	cosolvent	cell	product distribution,[b] % 4	5
controlled potential[c]	none	2 compt	54	0
controlled potential[c]	0.2 MH_2O	2 compt	49	3
controlled current[d]	none	2 compt	52	0
controlled current[d]	none	1 compt	22	0
controlled current[d]	0.2 M *i*-PrOH	1 compt	48	8

[a] The amount of reactant 1 was 28–90 mmol and the amount of charge transferred was in the range of 1.7–2.5 F mol^{-1}. [b] Determined by calibrated GC. [c] −2.80 V (SCE). [d] 4–8.5 mA cm^{-2}.

(1) Shono, T.; Mitani, M. *J. Am. Chem. Soc.* **1971**, *93*, 5284. Shono, T.; Nishiguchi, I.; Ohmizu, H. *Chem. Lett.* **1976**, 1233. Shono, T.; Nishiguchi, I.; Ohmizu, H.; Mitani, M. *J. Am. Chem. Soc.* **1978**, *100*, 545. Shono, T.; Kise, N.; Suzumoto, T.; Morimoto, T. *J. Am. Chem. Soc.* **1986**, *108*, 4676.

(2) Kariv-Miller, E.; Pacut, R. I.; Lehman, G. K. *Top. Curr. Chem.* **1988**, *148*, 97. Swartz, J. E.; Mahachi, T. J.; Kariv-Miller, E. *J. Am. Chem. Soc.* **1988**, *110*, 3622. Swartz, J. E.; Kariv-Miller, E.; Harrold, S. J. *J. Am. Chem. Soc.* **1989**, *111*, 1211.

(3) Curran, D. P. *Synthesis* **1988**, 47, 489. Giese, B. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 553.

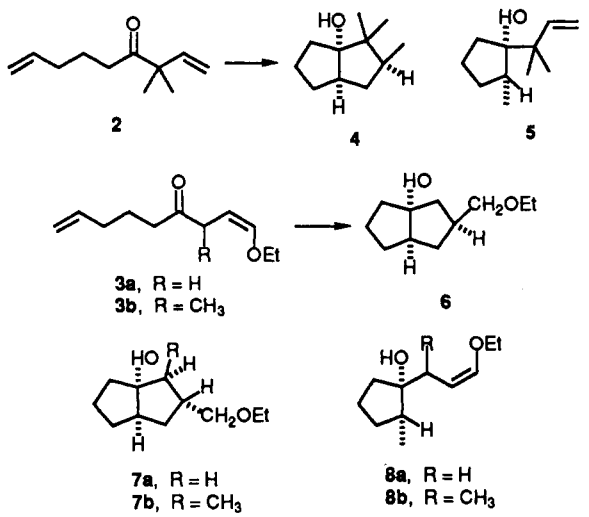
(4) Fevig, T. L.; Elliot, R. L.; Curran, D. P. *J. Am. Chem. Soc.* **1988**, *110*, 5064.

0022-3263/89/1954-4022$01.50/0

is for a samarium iodide reaction in which an aldehyde cyclizes onto a preformed cyclopentene, which then attacks a pendant alkyne to form a triquinane.

As model substrates for the exploration of this hypothesis, 3,3-dimethyl-1,8-nonadien-4-one (**2**) and (*Z*)-1-ethoxy-1,8-nonadien-4-one (**3a**) were chosen. The structure of these compounds precluded undesired isomerization to α,β-enones during the cathodic process. Compound **2** was prepared from 5-hexenal by alkylation[5] with 3-methyl-2-butenyl chloride followed by DMSO–P_2O_5 oxidation.[6] The condensation of 5-hexenal with allyl ethyl ether[7] in the presence of *sec*-BuLi, followed by pyridinium dichromate oxidation,[8] afforded **3a**.

Cathodic reduction of **2** using a Hg pool cathode, a platinum anode, DMF solvent, and Bu_4NBF_4 electrolyte gave the desired product **4**. Results obtained at various conditions are shown in Table I. At a constant potential of −2.80 V (SCE) in a divided cell **4** was the only product and was isolated pure in 54% yield (0.5-g scale) by mere extraction of the catholyte. For a large-scale synthesis controlled current conditions and undivided cell are advantageous, and this succeeded with 0.2 M 2-propanol as a cosolvent. Under these conditions a small amount of monocyclic alcohol **5** was also formed but was easily separated by flash chromatography. Electrolysis of 1 g of reactant at a constant current in an undivided cell yielded 0.5 g of pure **4**.



The structure of **4** was confirmed spectroscopically and the NMR spectrum showed that it was one isomer, which has been provisionally assigned to have the 3-methyl trans to the 1-hydroxy. Since chemical shifts and vicinal coupling constants in **4** are of little use for stereochemical assignment and NOE results were equivocal, recourse was made to the use of lanthanide shift reagent.[9] For this purpose the methyl ether of **4** was prepared. The methine (C-3) proton was established to be the most downfield proton in the multiplet (4 H) centered at about 1.6 ppm by means of a COSY spectrum. It was still the most downfield proton, in the same multiplet, at the end of a series of $Eu(Fod)_3$ additions as determined again by means

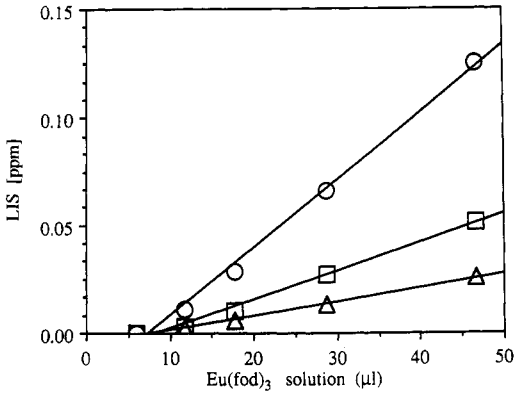


Figure 1. Dependence of the lanthanide-induced shifts [LIS] vs added amount of $Eu(fod)_3$ (0.487 M solution in $CDCl_3$). (○), CH_3O; (□), CH (C-3); (△), CH_3 (substituent at C-3).

of a COSY spectrum. The lanthanide induced shifts for the C-3 methine, C-3 methyl and *O*-methyl are shown in Figure 1. It can be seen the correlation is excellent, and the slopes indicate that the methine proton is shifted more rapidly than the C-3 methyl protons which in turn suggests a trans *O*-methyl/C-3 methyl configuration.

The product **5** was identified by comparison with a standard prepared by reaction[5] of 2-methylcyclopentanone with 3-methyl-2-butenyl chloride in the presence of Zn powder. In this reaction the nucleophile is thought to attack the ketone from the less hindered side, opposite the 2-methyl. The structure of **5** is in agreement with the idea that ketyl cyclization can give two isomeric radicals, one goes on to **4**, the other, in which the dimethylallyl and methylene are trans, cannot cyclize and terminates as **5**.

Compound **3a** also cyclized. In this case constant current, an undivided cell, and 0.2 M 2-propanol in DMF with 0.1 M Bu_4NBF_4 were used. Three products **6** (23%), **7a** (14%), and **8a** (20%) resulted. The monocyclic compound **8a** had the same stereochemistry as **5**, while **6** and **7a** were the desired bicyclooctanols. The configurations of **6** and **7a** were assigned by comparison of the ^1H NMR shifts[10] of the CH_2OEt and R_f values on TLC.[11] The peak of the doublet for **7a**, which is less polar by TLC than **6** appears at 3.36 ppm (J = 5.0 Hz), whereas **6** has a doublet at 3.26 (J = 6.4 Hz). By analogy to 3-methylcyclopentanols, **7a** is assigned to have the ethoxymethyl cis to the hydroxy. The total yield of bicyclic product from **3a** was reasonable (37%). However, bicyclization can be more useful if it can be directed to yield a single bicyclic isomer. We thought that this can be achieved by proper substitution of the parent compound. For this purpose **3b** was prepared (by methylation of **3a**), and it was reduced under the conditions used for **3a**. The reduction products and yields of **3b** resembled those of **3a** and consisted of 39% bicyclic and 20% monocyclic alcohols. However the bicyclic product of **3b** was a single isomer. The structure of this product was shown to be **7b**, by comparison with ^{13}C NMR of a series of substituted 2-methylbicyclo[3.3.0]octanes.[12]

Thus, the results confirm our initial hypothesis and show that cathodic reductive bicyclization is efficient and useful. The stereochemistry of the bicyclic products seems to depend on the balance between kinetic and thermodynamic factors and may be directed by proper design of the reactants. Preliminary results with two more reactants of type **3** show high yield of bicyclization, indicating the methodology is rather general. Since dienones like **2** and

(5) Petrier, C.; Einhorn, J.; Luche, J. L. *Tetrahedron Lett.* **1985**, 1449.
(6) Taber, D. F.; Amedio, J. C., Jr.; Jung, K.-Y. *J. Org. Chem.* **1987**, *52*, 5621.
(7) Evans, D. A.; Andrews, G. C.; Buckwalte, B. *J. Am. Chem. Soc.* **1974**, *96*, 5560.
(8) Czernecki, S.; Georgoulis, C.; Stevens, C. L.; Vijayakumaran, K. *Synth. Commun.* **1986**, 11.
(9) Raber, D. J. In *Lanthanide Shifts Reagents in Stereochemical Analysis*; Morrill, T. C., Ed.; VCH: New York, 1986; p 55. Paasivirta, J. *Ibid.* p 107.
(10) Rei, M.-H. *J. Org. Chem.* **1978**, *43*, 2173.
(11) Corey, E. J.; Pyne, S. G. *Tetrahedron Lett.* **1983**, 2821.
(12) Whitesell, J. K.; Matthews, R. S. *J. Org. Chem.* **1977**, *42*, 3878.

3 can be obtained in two or three steps from commercial materials, the approach looks valuable for synthesis.

Acknowledgment. Financial support of this project by the National Science Foundation is gratefully acknowledged.

Supplementary Material Available: Spectroscopic information for compounds **4**, **6**, and **7a** (1 page). Ordering information is given on any current masthead page.

Rearrangement of 4-Chloro-4-aryl(or alkenyl)cyclobutenones to *p*-Chlorophenols

Simon L. Xu and Harold W. Moore*

Department of Chemistry, University of California, Irvine, California 92717

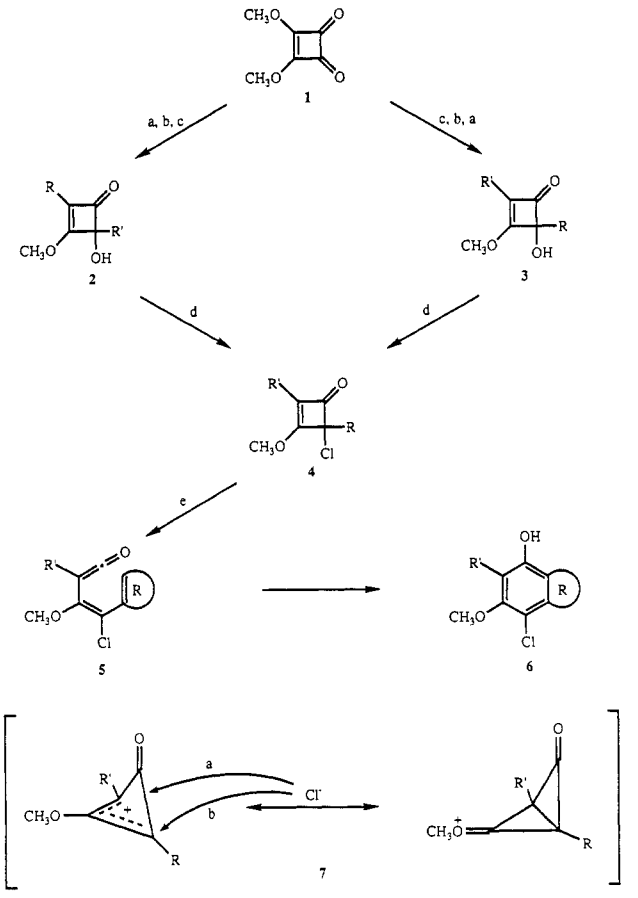
Received April 27, 1989

Summary: The synthesis and thermolysis of 4-chloro-4-aryl(or alkenyl)cyclobutenones is described. This results in a general and synthetically useful route to highly substituted chlorophenols and chloronaphthols. The chlorocyclobutenones were prepared from the related 4-hydroxy derivatives upon treatment with thionyl chloride in the presence of pyridine. The chlorination is regiospecific and predictable based upon a proposed mechanistic paradigm.

Sir: Previously, ring expansions of 4-alkynyl-4-hydroxy- and 4-aryl-4-hydroxycyclobutenones to respectively 1,4-benzoquinones and annelated hydroquinones were reported.[1,2] An extension of these rearrangements is now presented which shows that the thermolysis of 4-chloro-4-aryl(or alkenyl)cyclobutenones provides an efficient regiospecific route to substituted chlorophenols and chloronaphthols. The regiospecificity associated with this methodology is of particular interest and evolves from the overall transformation outlined in Scheme I. That is, starting with dimethylsquarate, **1**, the regioisomeric cyclobutenones **2** and **3** can be independently prepared.[3,4] *Interestingly, both of these cyclobutenones give the same 4-chloro derivative 4 upon treatment with thionyl chloride in methylene chloride and in the presence of pyridine, and the position of chlorination is predictable and dependent upon the substituents R and R'.* Thermolysis of **4** in refluxing *p*-xylene results in selective electrocyclic ring opening to the intermediate conjugated ketene **5**, which leads to the chlorophenols (or naphthols) **6** upon electrocyclic ring closure.

The selectivity of the chlorination of **2** and/or **3** is of particular note and deserves further comment. The results show that the substituents at positions 2 and 4 of the cyclobutenones **2** and **3** significantly influence the regiochemistry of the chlorination. Specifically, since the respective pairs of cyclobutenones give the same 4-chloro derivative, a common intermediate is obvious, and this is assumed to be the cationic species represented by structure **7**, a homoaromatic carbocation which should gain additional stabilization by electron donation of the methoxy substituent.[5,6]

Scheme I[a]



[a] Reagents: (a) RLi, THF, −78 °C; (b) TFAA/H$^+$; (c) R'Li, THF, −78 °C; (d) $SOCl_2$/pyridine, CH_2Cl_2, 0 °C; (e) *p*-xylene, 138 °C.

A very useful prediction of the site of chlorination evolves by further consideration of this paradigm. *That*

(1) (a) Karlsson, J. O.; Nguyen, N. V.; Foland, L. D.; Moore, H. W. *J. Am. Chem. Soc.* **1985**, *107*, 3392. (b) Foland, L. D.; Karlsson, J. O.; Perri, S. T.; Schwabe, R.; Xu, S. L.; Patil, S.; Moore, H. W. *J. Am. Chem. Soc.* **1988**, *111*, 975.

(2) (a) Moore, H. W.; Perri, S. T. *J. Org. Chem.* **1988**, *53*, 996. (b) Perri, S. T.; Foland, L. D.; Decker, O. H. W.; Moore, H. W. *J. Org. Chem.* **1986**, *51*, 3067. (c) Liebeskind, L. S.; Jewell, C. F.; Iyer, S. *J. Org. Chem.* **1986**, *51*, 3065.

(3) Reed, M. W.; Pollart, D. J.; Perri, S. T.; Foland, L. D.; Moore, H. W. *J. Org. Chem.* **1988**, *53*, 2477.

(4) Liebeskind, L. S.; Fengl, R. W.; Wirtz, K. R.; Shawe, T. T. *J. Org. Chem.* **1988**, *53*, 2482.

(5) (a) For analogies to this intermediate, see: Olah, G. A.; Staral, J. S. *J. Am. Chem. Soc.* **1976**, *98*, 6290. (b) Sprenger, H. E.; Ziegenbein, W. *Angew. Chem., Int. Ed. Engl.* **1968**, *7*, 530.

(6) (a) Olah, G. A.; Bollinger, J. M.; White, A. M. *J. Am. Chem. Soc.* **1969**, *91*, 3667. (b) Prakash, G. K. S.; Krishnamurthy, V. V.; Gergas, R.; Bau, R.; Yuan, H.; Olah, G. A. *Ibid.* **1986**, *108*, 836. (c) Jespersen, K. K.; Schleyer, P.; Pople, J. A.; Cremer, D. *Ibid.* **1978**, *100*, 4301. (d) Olah, G. A.; Mateescu, G. D. *Ibid.* **1970**, *92*, 1430. (e) Clark, T.; Wilhelm, D.; Schleyer, P. *Tetrahedron Lett.* **1982**, 3547.

0022-3263/89/1954-4024$01.50/0