# SYNTHESIS OF OXYGEN-CONTAINING HETEROCYCLES USING PALLADIUM(II) CATALYSTS

Takahiro Hosokawa* and Shun-Ichi Murahashi*

Department of Chemistry, Faculty of Engineering Science, Osaka University, Machikaneyama, Toyonaka, Osaka 560, Japan

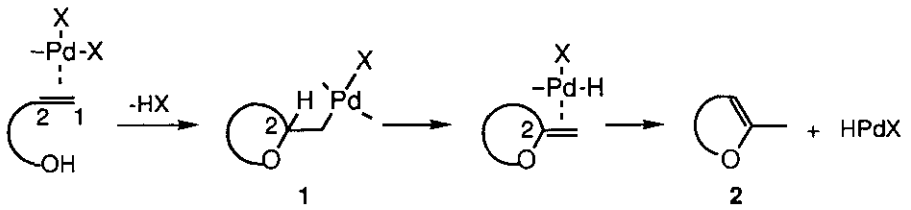
**Abstract** — Alkenes, dienes, and alkynes bearing hydroxy groups, when treated with palladium(II) catalysts, afford a variety of oxygen-containing heterocycles *via* cyclizations involving intramolecular oxypalladation as a key step. Trapping the oxypalladation intermediates with CO also creates useful entries to oxygen-containing heterocycles. Synthetic aspects of these cyclizations as well as the catalyses of palladium(II) are surveyed in this article.

A novel strategy for synthesizing heterocycles under mild conditions is provided by the use of metal complex catalysts. Among those, palladium complexes undoubtedly lie in a unique position in terms of its versatility and reactivity.[1] The reactivity of palladium complexes depends on their valency. Fundamentally, palladium(II) acts as Lewis acid, while nucleophilic nature is characteristic of palladium(0). The difference in valency is also important in constructing the catalysis of palladium. Since palladium(II) has inherently an oxidizing ability, it is generally reduced to palladium(0) during the reaction. Accordingly, in order to make catalytic transformations in palladium(II), reduced palladium(0) must be reoxidized into palladium(II). Alternatively, it should be devised to retain the valency of palladium(II) as +2 state during the reaction. Development of new catalytic reactions using palladium(II) is one of our interests, and hence recent advance of palladium(II)-catalyzed syntheses of oxygen-containing heterocycle are surveyed. In particular, focus is placed on cyclizations involving

intramolecular oxypalladation as a key step.[2,3] An aspect of the catalysis in palladium(II) is also one of the subjects in this article.

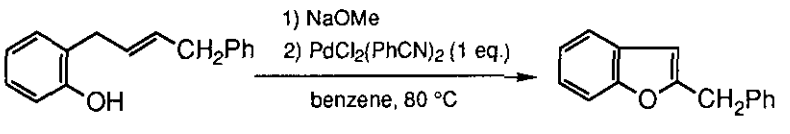
## Intramolecular Oxypalladation of Alkenes

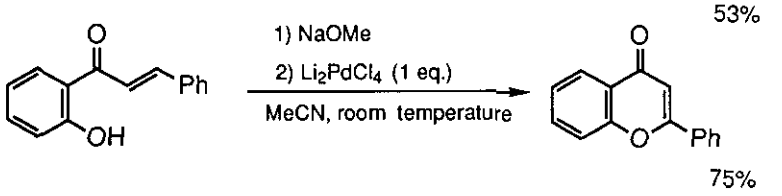
The fundamental chemistry of palladium(II) can be seen in oxidation of alkenes by $PdX_2$ (X=Cl or OAc), *in which nucleophiles such as* OH *and* OAc *first attack olefins coordinated to the metal, forming a* σ-bonded Pd(II)-intermediate. Subsequent β-elimination of Pd-H species leads to products, and the resulting Pd-H species decomposes to give Pd(0) and HX. The oxidation of terminal alkenes to methyl ketones is a typical example of this chemistry.[4] Intramolecular version of this reaction becomes a useful entry to oxygen-containing heterocycles as shown in Scheme 1, where the σ-bonded Pd(II) intermediate (**1**) is called an oxypalladation intermediate. β-Elimination of palladium hydride from this intermediate (**1**) usually results in the formation of products bearing alkenes in the more stable position *via* equilibriation.

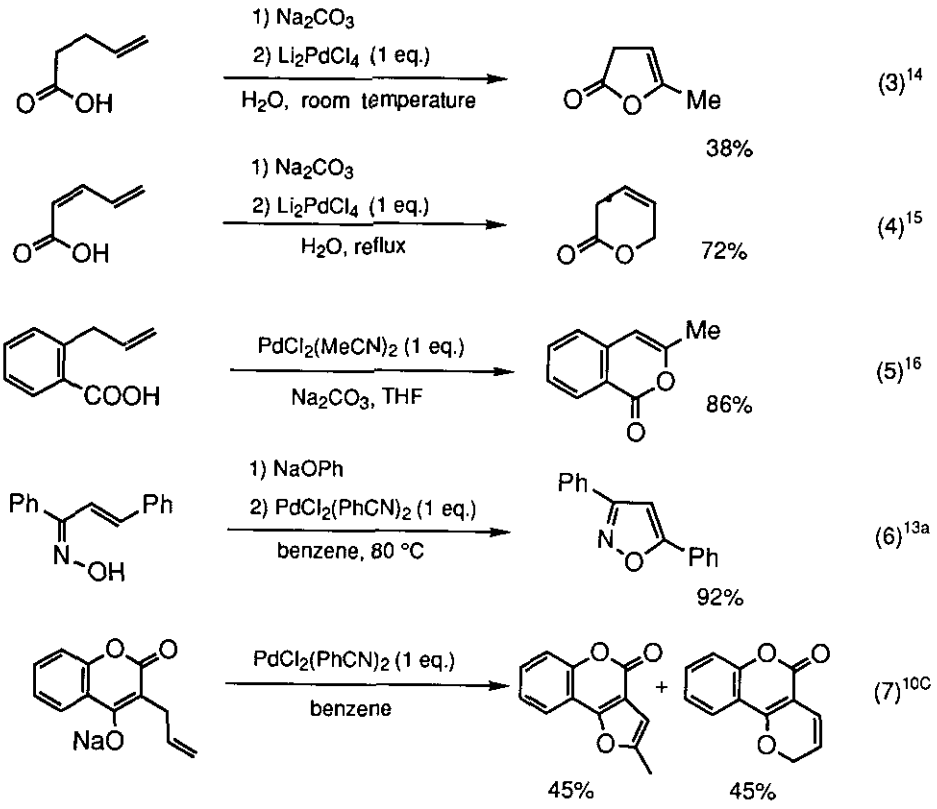



**Scheme 1**

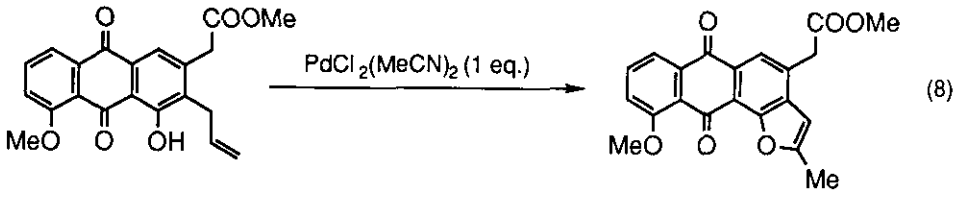
Alkenylphenols,[5-10] alcohols,[11,12] oximes,[13] and carboxylic acids[14-16] serve as substrates for this type of cyclization. Given in eqs. 1-7 are the fundamental reactions of these substrates with a stoichiometric



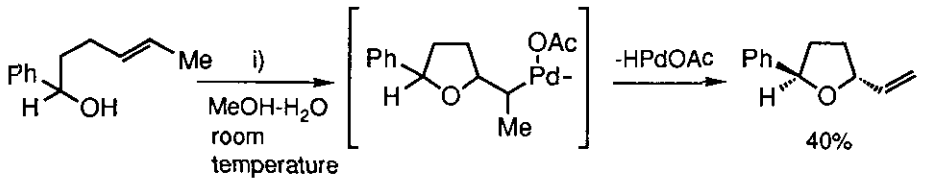





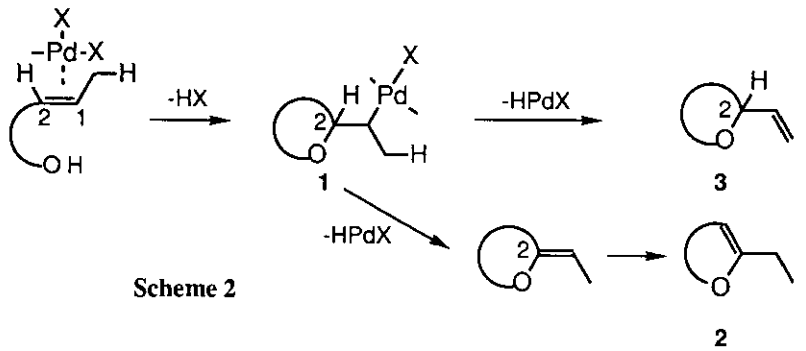

amount of Pd(II) salts. A benzofuran synthesis of the aklavinone system is also shown in eq. 8.[8] In principle, these cyclizations can be made catalytic with respect to palladium by the use of either a




combination of Cu(II) salts and $O_2$ or *p*-benzoquinone as oxidants. In fact, γ,δ-unsaturated alcohols can be catalytically converted into 2-vinyltetrahydrofurans (eq. 9), when $Pd(OAc)_2$ is used together with $Cu(OAc)_2$ and $O_2$.[11]

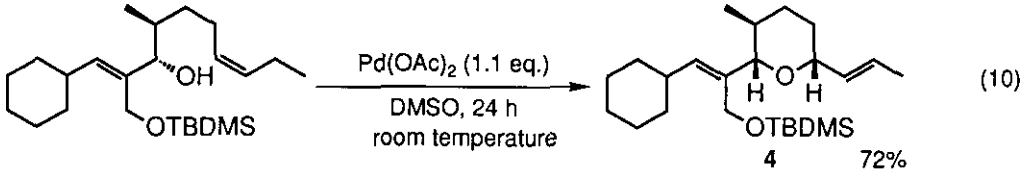



If the oxypalladation intermediate (**1**) has two possibilities of β-elimination of palladium hydride as shown in Scheme 2, β-hydrogen atom of the side chain is predominantly eliminated to give **3**, and equilibration of

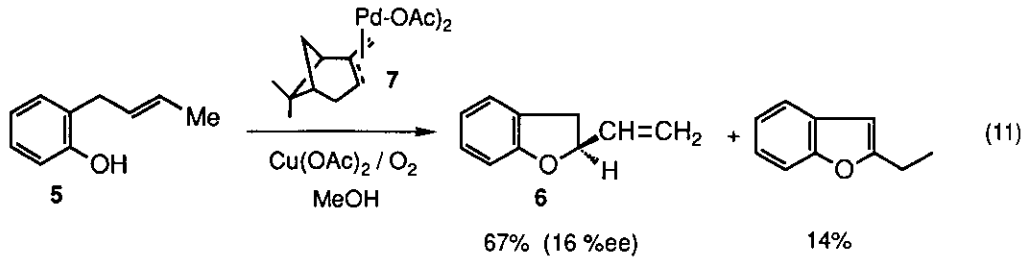



**Scheme 2**

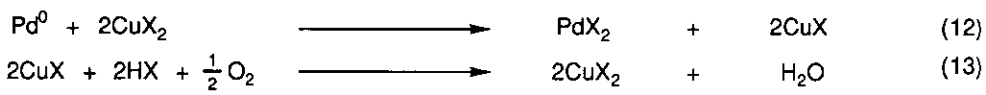
the resulting alkenes such as **3** and **2** is minimized by the use of $Pd(OAc)_2$. This is exemplified by the cyclization of eq. 9. Furthermore, when dimethyl sulfoxide (DMSO) is used as a solvent, the direction of β-palladium hydride elimination is effectively controlled, and this technique has allowed the selective synthesis of tetronomycin precursor (**4**) as shown in eq 10.[12]



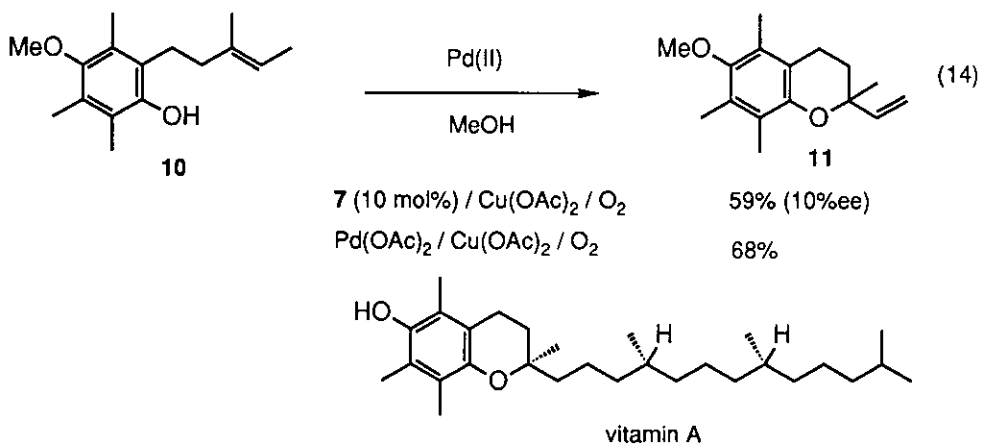

Among these cyclizations, we have firstly found that 2-(2-butenyl)phenol (**5**) is asymmetrically cyclized to give optically active 2-vinylbenzofuran (**6**) by the use of optically active $[(\eta^3\text{-pinene})Pd(OAc)]_2$ (**7**) as the catalyst with $Cu(OAc)_2$ and $O_2$ (eq. 11).[17] Although the enantioselection was not high (16 %ee),

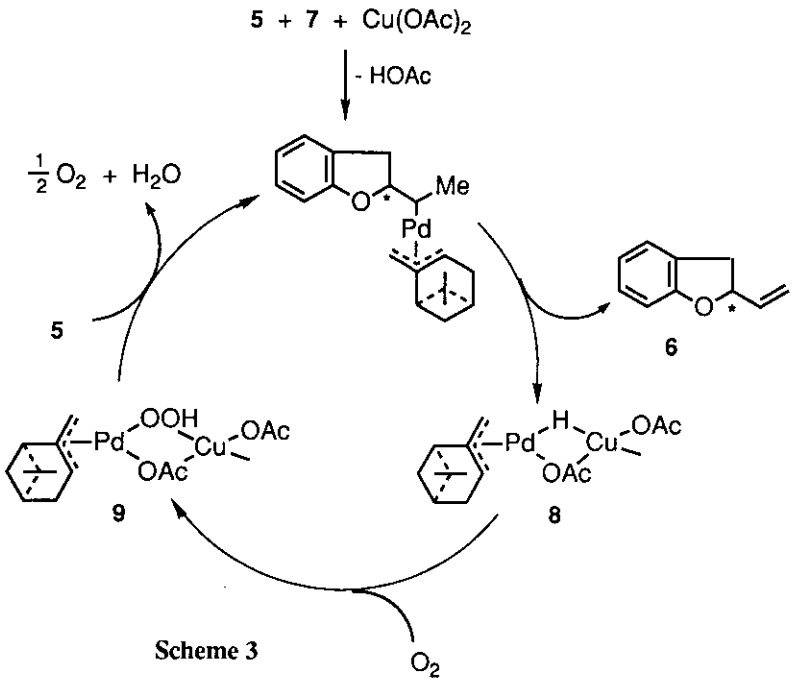



interestingly, the pinanyl ligand of Pd(II) was intact during the reaction. Furthermore, the rate of cyclization becomes faster as the relative ratio of added $Cu(OAc)_2$ to **7** increases and reaches a maximum when Cu/Pd = 1. On the basis of these observations, we have proposed that as shown in Scheme 3, the resulting Pd-H species (**8**) coupled with Cu(II) salt reacts with $O_2$ to give a Pd-OOH (**9**) which acts as the active catalyst . If the PdHCl species (**8**) decomposes to Pd(0) and HCl, the conventional redox couple of eqs. 12 and 13 may accounts for the catalysis. However, this possibility can be ruled out, because the pinanyl ligand is retained on the palladium(II) throughout the reaction.



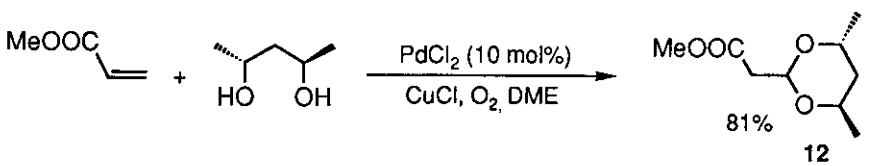

With this type of cyclization, the chroman moiety (**11**) of α-tocopherol (vitamin A) is able to be prepared from pentenylphenols (**10**) derived from commercially available 2,3,4-trimethylhydroquinone *via* 4 steps (eq. 14).[18]





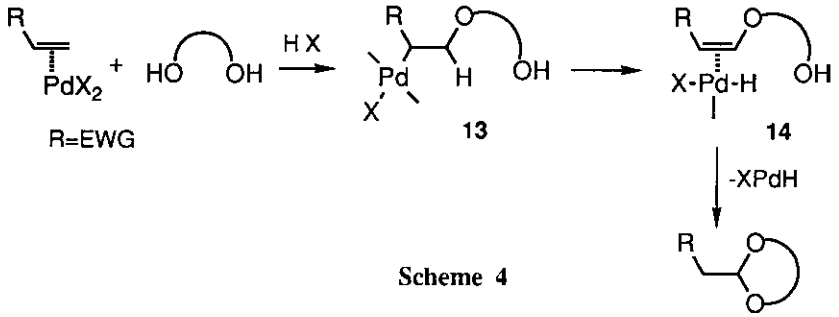

**Scheme 3**

Chiral 1,3-dioxanes which serve as useful precursors of asymmetric syntheses are prepared by Pd(II)-catalyzed acetalization of terminal alkenes bearing electron-withdrawing groups (EWG) with chiral 1,3-diols. A typical example given in eq. 15 shows that chiral acetal (**12**) can be readily prepared from methyl acrylate and (*R*,*R*)-2,4-pentanediol.[19] The reaction pathway leading to acetals again involves the fundamental chemistry of Pd(II) as shown in Scheme 4; nucleophilic addition of an OH group to the olefin



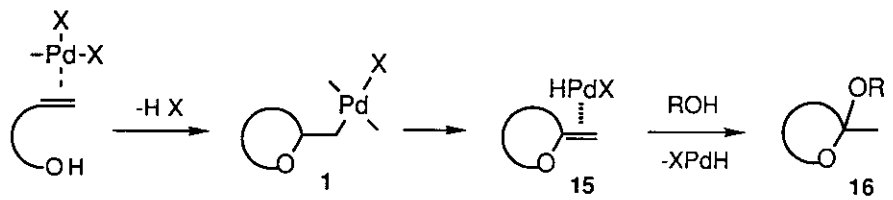

(15)

to give **13** and subsequent β-Pd-H elimination. The ring closure takes place *via* intramolecular addition of another OH group to the vinyl ether bond in **14**.



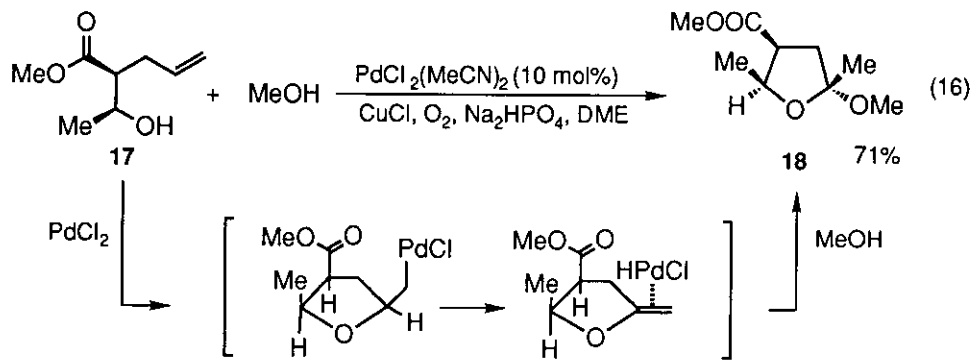

**Scheme 4**

Modification of the process extends the reaction into further useful entries to oxygen-containing heterocycles. Thus, intermolecular addition of alcohols to the intermediate alkenyl ethers (**15**) formed *via* oxypalladation gives acetals (**16**) with leaving HPdX (Scheme 5). Using this method, optically active

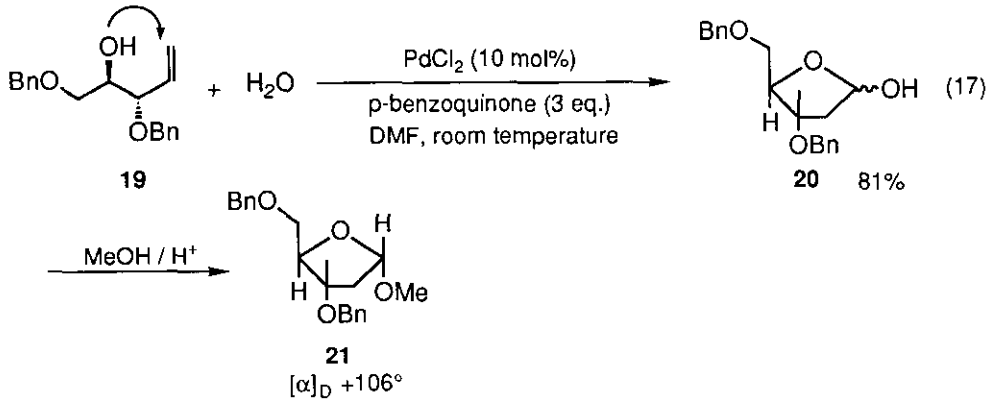



**Scheme 5**

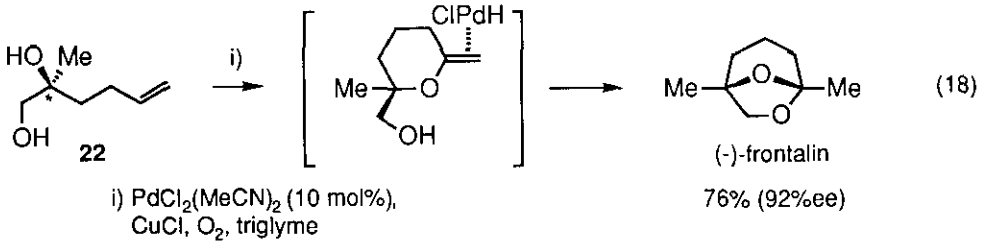
tetrahydrofuran (**18**) can be prepared from (2*S*,3*S*)-2-allyl-3-hydroxybutyrate (**17**) in 88 %de (eq. 16).[20] In this reaction, copper(I) chloride, not $CuCl_2$, is used together with $O_2$ as the oxidizing agent. Generally in Pd(II)-catalyzed ketonization of terminal alkenes with water,[4] CuCl pretreated with $O_2$ is used as the oxidant in order to suppress chlorination of carbonyl compounds.



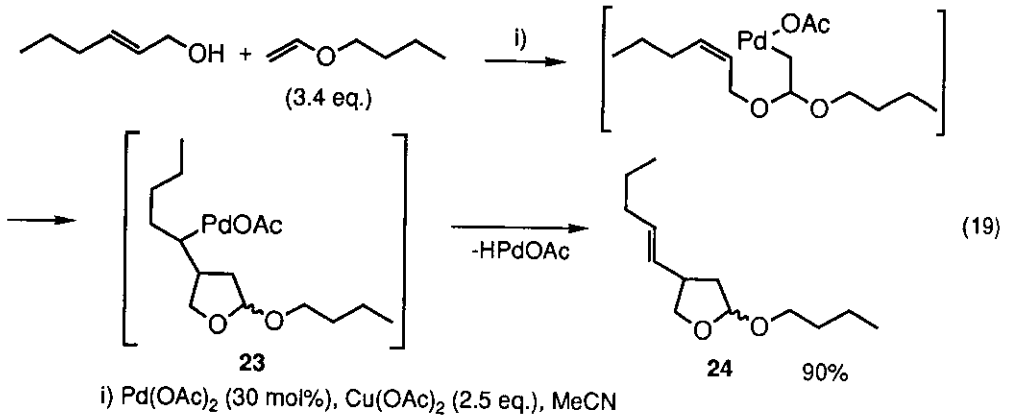
Trapping of the vinyl ethers (**15**) (Scheme 5) with water leads to hemiacetals. An interesting application of the reaction can be seen in the synthesis of protected deoxyribose (**21**) as the optically pure form (eq. 17),[21] in which excess amounts of *p*-benzoquinone is utilized as an oxidant for the catalytic cyclization of **19** to **20**.



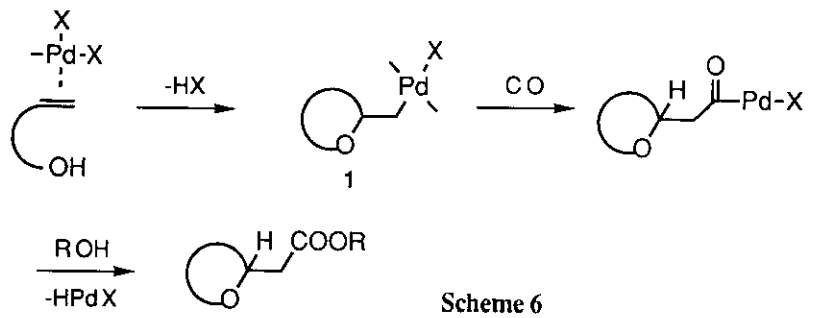

Intramolecular version of this reaction with alkenyl diols gives bicyclic acetals. Optically active natural (*S*)-(-)-frontalin can be synthesized from optically active (*S*)-alkenyl diol (**22**) by this method (eq. 18).[22] Unnatural frontalin is also prepared form the antipode of **22**.




A variant of the acetal synthesis is given in eq. 19 where addition of alkenyl alcohol to vinyl ether firstly takes place. Intramolecular insertion of the resulting Pd-C bond to olefin followed by β-elimination of palladium hydride from the resulting intermediate (**23**) affords furan (**24**).[23] The reaction also proceeds catalytically in the presence of excess amounts of $Cu(OAc)_2$.

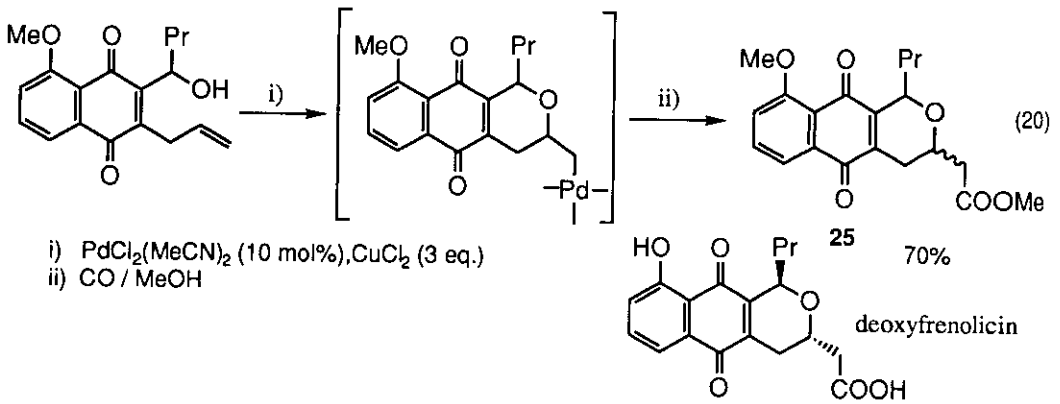



Insertion of CO into the Pd-C bond of oxypalladation intermediates (**1**) and subsequent attack by alcohols leads to oxygen-containing heterocycles bearing ester groups (Scheme 6). A fascinating example of

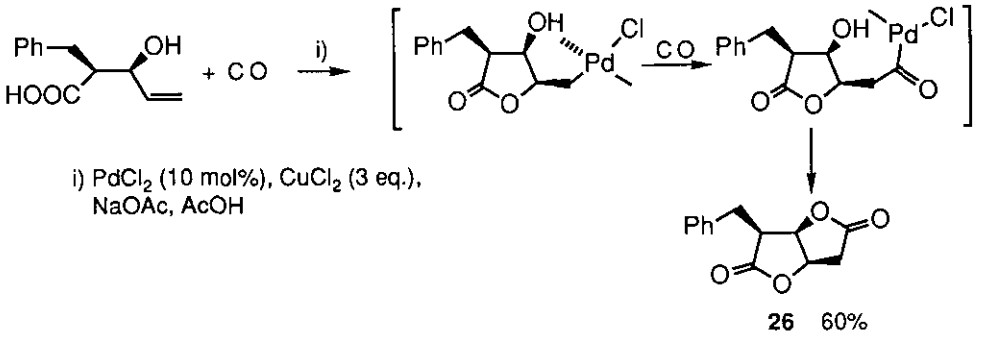



**Scheme 6**

this sequence can be seen in the synthesis of deoxyfrenolicin precursor (**25**) (eq. 20)[24] and related

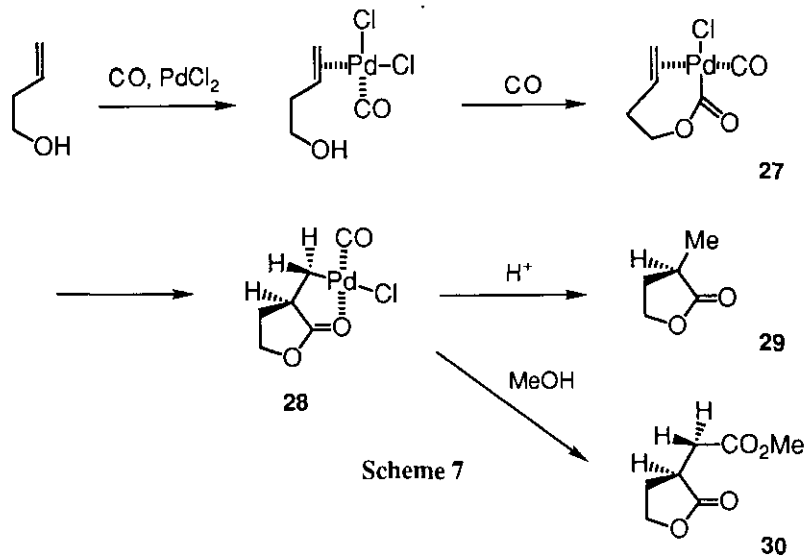


compounds.[25] Bislactone (**26**) is similarly synthesized *via* intramolecular carboxypalladation followed by carbonylation (eq. 21).[26] In these reactions, excess amounts of $CuCl_2$, instead of CuCl, is used as the oxidant.



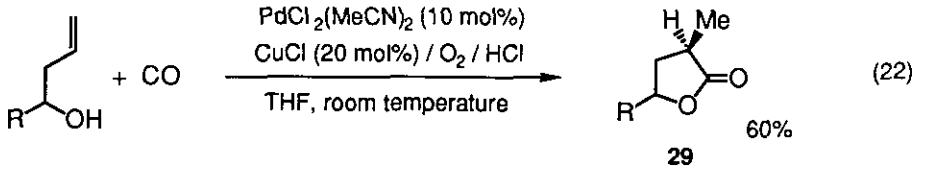

(21)

In these reactions using CO, alkoxypalldation (eq. 20) or carboxypalldation (eq. 21) takes place first, and then carbonylation is followed. However, when homoallyl alcohol (3-butene-1-ol) is subjected into similar conditions ($PdCl_2$, $CuCl_2$, and CO), the alkoxypalladation step is inhibited, probably owing to the ring strain of the expected oxetane product.[27] Instead, the OH group first attacks CO coordinated to Pd(II) to form palladium(II) carboxylate (**27**) (Scheme 7) which then cyclizes into lactones (**28**) containing a

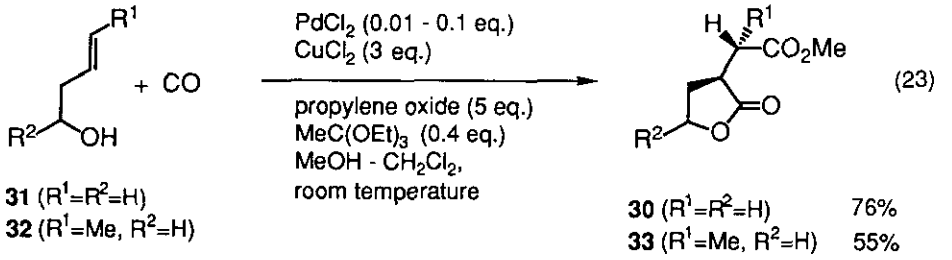



**Scheme 7**

Pd-C bond. Depending on reaction conditions used, the fate of **28** is determined. Thus, under acidic conditions (HCl, $O_2$, and THF),[28] protonolysis of the C-Pd bond leads to α-methyl-γ-butyrolactone (**29**). This carbonylation is a so-called intramolecular hydroesterification.[29] Under neutral conditions (propylene oxide and triethyl orthoacetate),[27] dicarbonylation takes place to give lactone esters (**30**). The representative examples as well as reaction conditions are given in eqs. 22 and 23. The dicarbonylation in eq. 23 has proved to proceed *via cis*-addition (**32** → **33**), and lactonizations of this type have wide

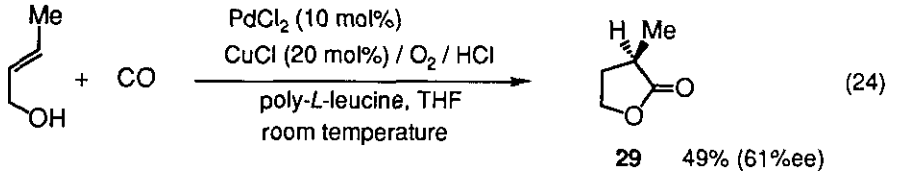



(22)




(23)

applicability to homoallyl alcohols. Under basic conditions ($C_3H_7COONa$, $CuCl_2$, MeOH), no cyclized product is formed from 3-butene-1-ol.[30] Under acidic conditions, allyl alcohols (2-butene-1-ols) are similarly converted into γ-butyro-lactones.[31] In the presence of poly-L-leucine (M 21700; DP=192), a 61 % ee of optically active (*R*)-**29** is obtained from 2-buten-1-ol in 49% yield (eq. 24).[32]

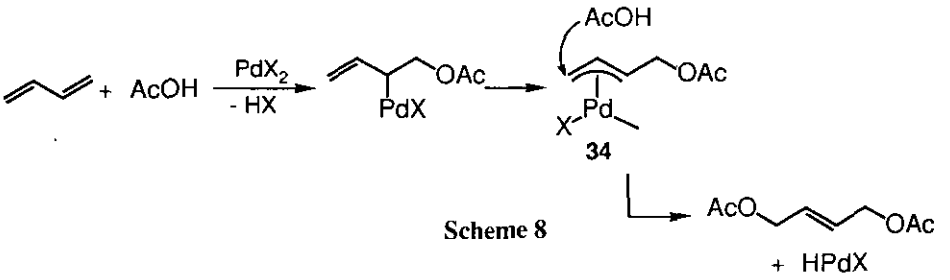



(24)

**Intramolecular Oxypalladation of Dienes**

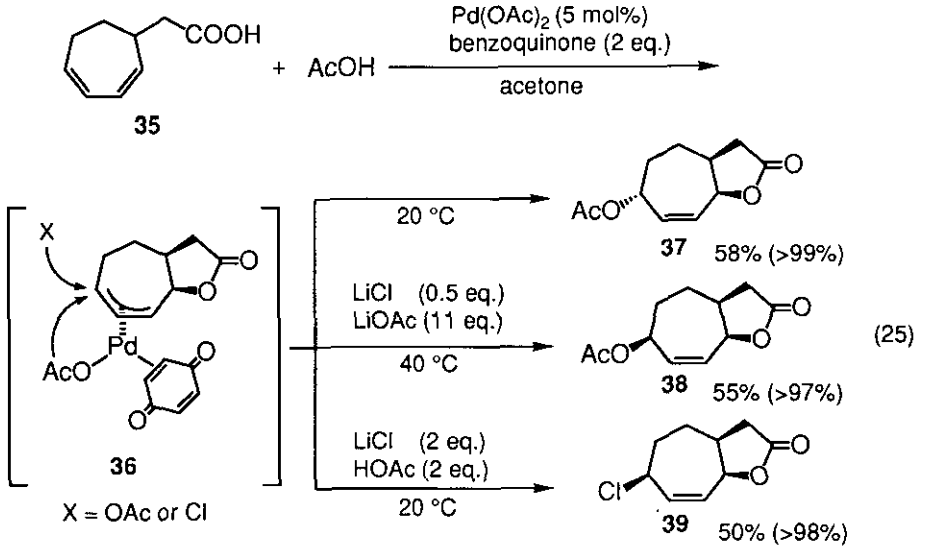
Butadiene, when treated with acetic acid in the presence of Pd(II) catalyst, is transformed into 1,4-diacetoxy-2-butene.[33] The reaction proceeds *via* acetoxypalladation of the olefin leading to (π-

allyl)palladium(II) intermediate (**34**) (Scheme 8). Subsequent nucleophilic attack by another AcOH to the intermediate (**34**) affords 1,4-diacetoxybutene together with XPdH (or Pd(0) + HX). This type of 1,4-di-




**Scheme 8**

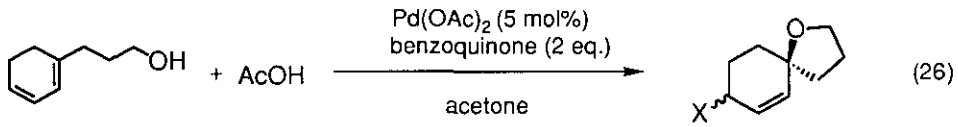
functionalization of conjugated dienes has been extensively studied by Bäckvall,[34] and intramolecular version of the reaction becomes a useful entry to oxygen-containing heterocycles. Given in eq. 25 is a typical example of the cyclization using dienyl carboxylic acid (**35**), in which $Pd(OAc)_2$ is used as the catalyst with *p*-benzoquinone and AcOH.[35] The reaction proceeds *via* first carboxypalladation and subsequent attack of AcOH on a π-allylpalladium(II) intermediates (**36**). The second nucleophilic attack is




(25)

thought to be facilitated by coordination of an electron-withdrawing ligand of *p*-benzoquinone to palladium(II). Of particular interest in this intramolecular 1,4-difunctionalization is that the course of cyclization is dramatically controlled by additives. Thus, without using additives, the AcO ligand in **36** internally attacks the π-allyl moiety in a *cis* fashion, resulting in 1,4-*trans* addition leading to bicyclic lactone (**37**), since the first carboxypalladation step occurs in a *trans*-manner. On the other hand, the use of catalytic amounts of LiCl, in addition to LiOAc, results in 1,4-*cis* addition leading to **38**, because the second addition of AcOH takes place externally. At a higher chloride concentration, external attack of $Cl^-$ on **36** results in *cis*-1,4-chlorolactonization to give **39**.

Similar results are obtained with conjugated dienes bearing a hydroxyalkyl side chain such as shown in eq. 26 where spiroethers are formed stereoselectively.[36,37] Generally in the 1,4-difunctionalization of



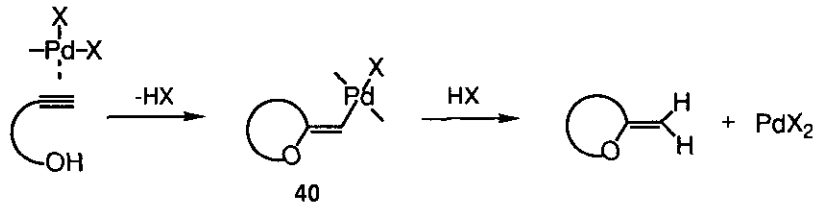

(26)

$Li_2CO_3$ (3 eq.), X=OAc 86% (>98% trans)
LiCl (1.8 eq.) , X=Cl 73% (>98% trans)

conjugated dienes, stoichiometric or more excess amounts of *p*-benzoquinone is used as the oxidant as well as the ligand of intermediate palladium(II) complex as mentioned above. However, the reaction can be made to be catalytic even with respect to *p*-benzoquinone if a stoichiometric amount of $MnO_2$ is used.[38,39]

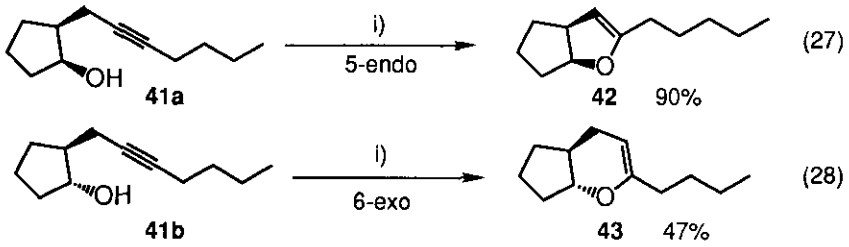
**Intramolecular Oxypalladation of Alkynes**

Pd(II)-catalyzed cyclization of alkynes bearing hydroxy [40] and carboxyl[41,42] groups also provides a useful entry to various heterocycles. Alkenyl palladium(II) intermediate (**40**) arising from intramolecular addition of protic group to acetylenic bond (Scheme 9) does not undergo β–hydride elimination. Instead, protonolysis of the Pd-C bond in **40** results in the formation of vinyl ethers. Since $PdX_2$ is regenerated



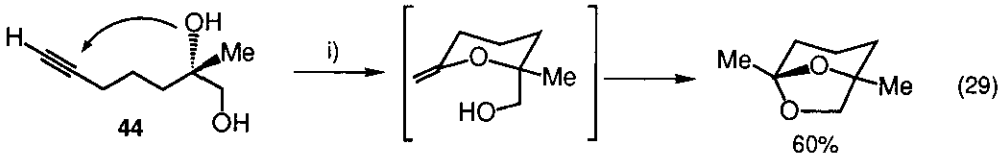

**Scheme 9**

after the completion of reaction, no aid is required for the catalysis of palladium. Examples of the sequence given in eqs. 27 and 28[40] show that *cis*-acetylenic alcohol (**41a**) gives *cis*-dihydrofuran (**42**), while *trans*-(**41b**) leads to thermodynamically favorable 6-*endo* cyclized product (**43**). Mercury (II) salts similarly catalyzes the cyclization of this type.[43]



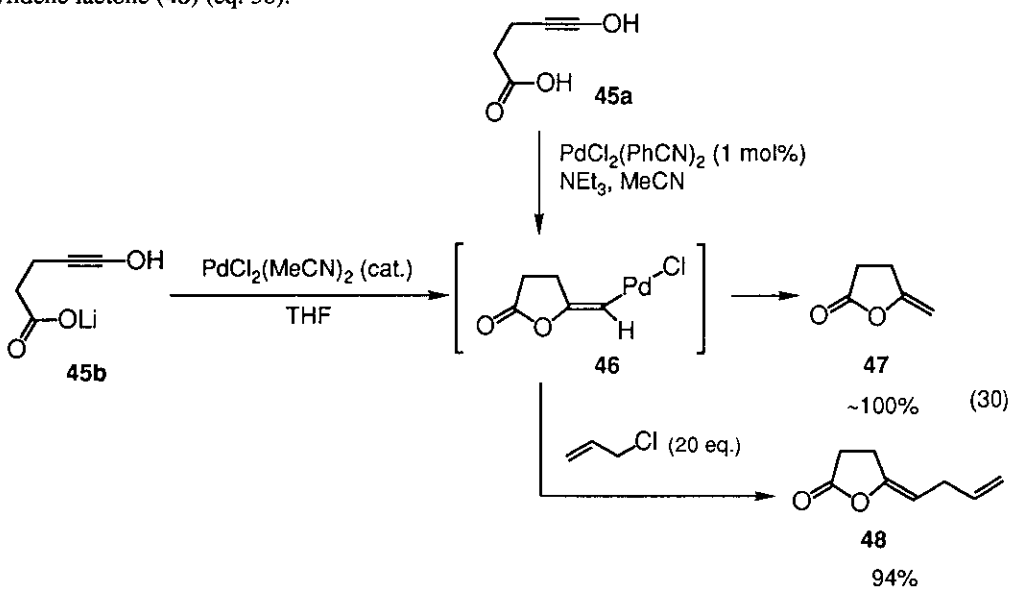

i) $PdCl_2(PhCN)_2$ (1 mol%), $Et_2O$, room temperature

Alkynes bearing two hydroxy groups at appropriate positions give intramolecular acetals *via* addition of an OH group to carbon-carbon triple bond followed by further addition of another OH group to the vinyl ether bond formed. An example can be seen in the synthesis of frontalin from optically active 6,7-dihydroxy-6-methyl-1-heptyne (eq. 29).[40]

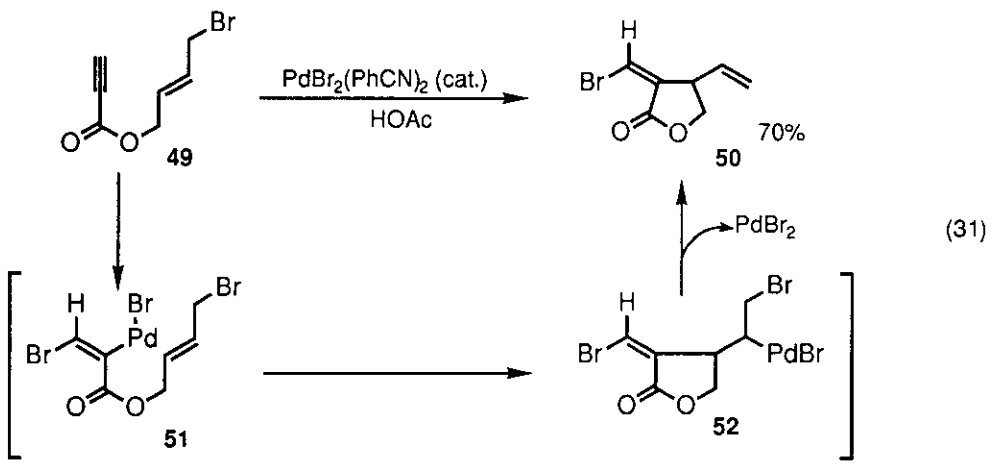



i) $PdCl_2(PhCN)_2$ (1 mol%), THF

Alkynes bearing COOH group also undergo the same type of cyclization, and a synthesis of *exo*-enol lactones (**47**) can be attained from 4-pentynoic acids (**45a**).[41,44] Trapping the intermediate alkenyl palladium(II) (**46**) derived from **45b** by electrophiles such as allyl chloride results in the formation of alkylidene lactone (**48**) (eq. 30).[42a]

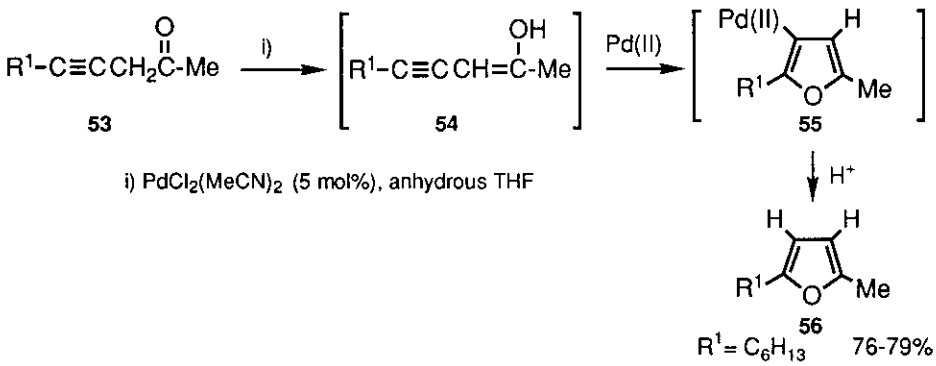



A strategy for trapping the intermediate σ–alkenyl palladium(II), arising from addition of $PdX_2$ to alkynes, by allyl chloride was first developed for synthesizing halogeno-substituted 1,4-diene codimers.[45] As



shown in eq. 31, intramolecular variant of this reaction has recently proved to be useful for synthesizing α-(Z)-halomethylene-γ-butyrolactone (**50**) from haloallylic 2-alkynoate (**49**).[46] The reaction proceeds *via* halopalladation of alkyne leading to **51** followed by insertion of the internal C=C bond to give **52**. β-Dehalopalladation in **52** predominates over β-hydride elimination, resulting in the formation of **50** with regeneration of $PdBr_2$ species. Therefore, no aid is again required for the catalysis.

β,γ-Acetylenic ketones (**53**) can be converted into substituted furans (**56**) upon treatment with $PdCl_2(MeCN)_2$ catalyst (eq. 32).[47] When anhydrous THF is used as solvent, the reaction is thought to proceed *via* oxypalladation of enol (**54**) followed by protodemetalation of **55** to give **56**.

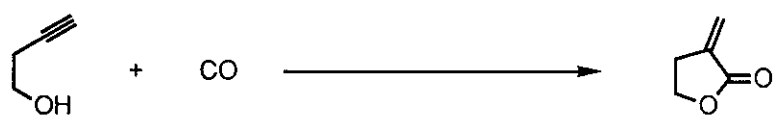



53 54 55 56

i) $PdCl_2(MeCN)_2$ (5 mol%), anhydrous THF (32)

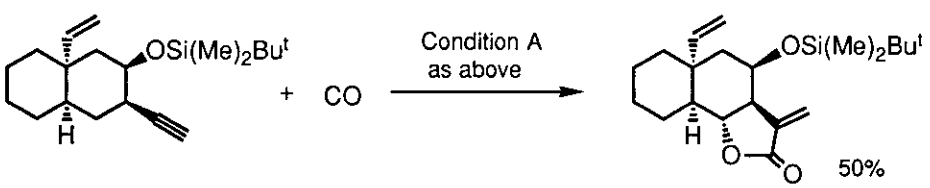
$R^1 = C_6H_{13}$ 76-79%

Carbonylation of hydroxyalkynes again constructs lactone syntheses. A pioneer work of Norton in this field has developed the synthetic method of α-methylene-γ-butyrolactone from 3-butyne-1-ol as shown in eq. 33.[48] With this method, a sesquiterpene antitumor lactone has been synthesized by Heathcock



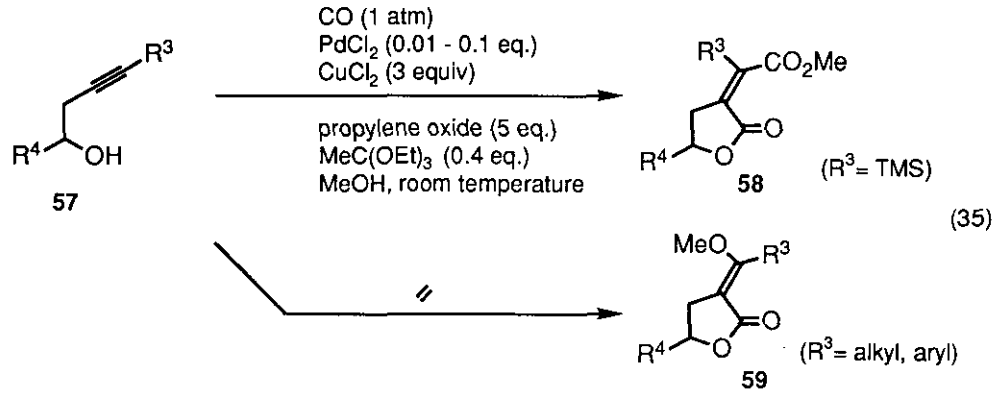

A) $PdCl_2$ (5 mol%), thiourea (5 mol%), acetone 21%

B) $PdCl_2$ (1.6 mol%), $SnCl_2$ (1.6 mmol), $PPh_3$, $CH_3CN$ 91% (33)



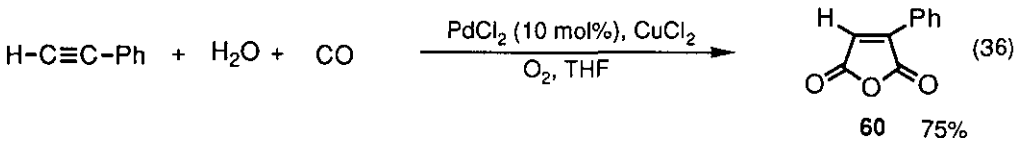

50% (34)

(eq. 34).[49] A catalyst system of $PdCl_2$ and thiourea has later improved to use a combination of $PdCl_2$, $SnCl_2$, and triphenylphosphine which has become an efficient tool for synthesizing the γ-butyrolactones. Recently, 3-butyne-1-ol derivatives (**57**) have been shown to undergo either dicarbonylation to **58** or methoxycarbonylation to **59** (eq. 35), depending on the substituents on the acetylenic carbon, under the same conditions as those described in eq. 23.




(35)

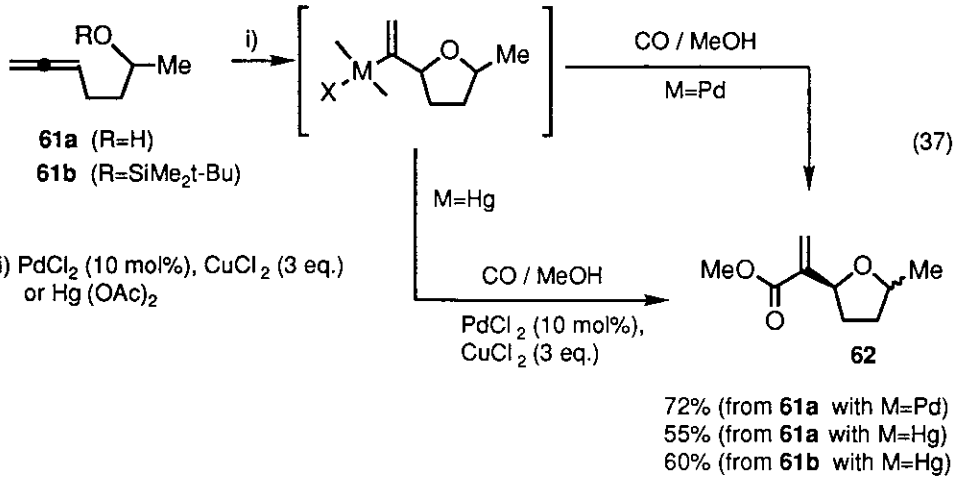
A system consisting of $PdCl_2$ / $CuCl_2$ / CO / $O_2$ / HCl mentioned before catalyzes various carbonylation of alkynes in the presence of oxygen nucleophiles such as water and alcohols.[50] When phenylacetylene was subjected into the system with water and/or formic acid, phenyl substituted maleic anhydride (**60**) is formed in 75% yield.[51] When substituents are introduced on the acetylenic carbon, the corresponding maleic and fumaric acids are concurrently formed.




(36)

Allenes (**61**) bearing a hydroxy or a trialkylsiloxy group γ to the allene moiety undergo intramolecular oxypalladation-carbonylation under the conditions using $PdCl_2$, $CuCl_2$; and CO in methanol, affording a 1 : 1 mixture of two stereoisomeric 2-(2-tetrahydrofuryl)acrylates (**62**) (eq. 37).[52] When allene (**61b**)

bearing a siloxy group was first treated with a stoichiometric amount of $Hg(OAc)_2$ and then the resulting complex was subjected into carbonylation using a catalytic amount of $PdCl_2$ in the presence of $CuCl_2$ and CO in methanol, *cis*-isomer of **62** was formed stereoselectively.




(37)

In summary, intramolecular oxypalladation of alkenyl compounds becomes useful approaches to the synthesis of oxygen-containing heterocycles. The reaction pathways follow the fundamental chemistry of palladium(II). In principle, alkenyl compounds bearing nitrogen nucleophiles undergo the same type of cyclization described in this article, and extensive studies have been performed to synthesize nitrogen-containing heterocycles.[53] Of course, palladium(0) catalysts effect a variety of cyclizations, those of which have been summarized in excellent accounts.[54]

## REFERECES AND NOTES

1. (a) J. Tsuji, 'Organic Synthesis with Palladium Compounds,' Springer-Verlag, Berlin, 1980. (b) B. M. Trost and T. R. Verhoeven, 'Comprehensive Organometallic Chemistry,' Vol. 8, ed. by G. Wilkinson, Oxford, 1982, pp. 854-983. (c) R. F. Heck, 'Palladium Reagent in Organic Syntheses,' Academic, New York, 1985. (d) P. M. Henry, 'Palladium Catalyzed Oxidation of Hydrocarbons,' Reidel, Dordrecht, 1980, pp. 41-84. (e) P. M. Maitlis, 'The Organic Chemistry of Palladium,' Vol. 2, Academic, New York, 1971, pp. 77-101.

2. T. Hosokawa and S.-I. Murahashi, Acc. Chem. Res., 1990, 23, 49.
3. For our another studies of heterocyclic syntheses using palladium catalysts; see (a) H. Onoue. I. Moritani, and S.-I. Murahashi, Tetrahedron Lett., 1973, 121 . (b) S.-I. Murahashi, Y. Mitsue, and K. Ike, J. Chem. Soc., Chem. Commun., 1978, 125 .
4. J. Tsuji, Synthesis, 1984, 369
5. T. Hosokawa, H. Ohkata, and I. Moritani, Bull. Chem. Soc. Jpn., 1975, 48, 1533; T. Hosokawa, K. Maeda, K. Koga, and I. Moritani, Tetrahedron Lett., 1973, 739.
6. A. Kasahara, T. Izumi, and M. Ooshima, Bull. Chem. Soc. Jpn., 1974, 47, 2526.
7. T. Hosokawa, S. Yamashita, S.-I. Murahashi, and A. Sonoda, Bull. Chem. Soc. Jpn., 1976, 49, 3662; T. Hosokawa, S. Miyagi, S.-I. Murahashi, and A. Sonoda, J. Org. Chem., 1978, 43 , 2752.
8. B. A. Pearlman, J. M. McNamara, I. Hasan, S. Hatakeyama, H. Sekizaki, and Y. Kishi, J. Am. Chem. Soc., 1981, 103, 4248.
9. T. Hosokawa, T. Kono, T. Uno, and S.-I. Murahashi, Bull. Chem. Soc. Jpn., 1986, 59, 2191.
10. (a) B. Cardillo, M. Cornia, and L. Merlini, Gazz. Chim. Ital., 1975, 105, 1151. (b) G. Casiraghi, D. Casnati, G. Puglia, G. Sartori, and G. Terenghi, Synthesis, 1977, 122. (c) R. J. Kumar, G. L. D. Krupadanam, and G. Srimannarayana, ibid., 1990, 535.
11. T. Hosokawa, M. Hirata, and S.-I. Murahashi, Tetrahedron Lett., 1976, 1821.
12. M. F. Semmelhack, C. R. Kim, W. Dobler, and M. Meier, Tetrahedron Lett., 1989, 37, 4925.
13. (a) K. Maeda, T. Hosokawa, S.-I. Murahashi, and I. Moritani, Tetrahedron Lett., 1973, 5057. (b) T. Hosokawa, N. Shimo, K. Maeda, A. Sonoda, and S.-I. Murahashi, Tetrahedron Lett., 1976, 383.
14. A. Kasahara, T. Izumi, K. Sato, M. Maemura, and T. Hayasaka, Bull. Chem. Soc. Jpn., 1977, 50, 1899.
15. T. Izumi and A. Kasahara, Bull. Chem. Soc. Jpn., 1975, 48, 1673.
16. D. E. Korte, L. S. Hegedus, and R. K. Wirth, J. Org. Chem., 1977, 42, 1329.
17. T. Hosokawa, T. Uno, S. Inui, and S.-I. Murahashi, J. Am. Chem. Soc., 1981, 103, 2318; see also T. Hosokawa, C. Okuda, and S.-I. Murahashi, J. Org. Chem., 1985, 50, 1282.
18. T. Hosokawa, T. Kono, and S.-I. Murahashi, unpublished results, and for a related reaction; see T. Hosokawa, T. Kono, T. Shinohara, and S.-I. Murahashi, J. Organomet. Chem., 1989, 370, C13.

19. T. Hosokawa, T. Ohta, S. Kanayama, and S.-I. Murahashi, J. Org. Chem, 1987, 52, 1758; see also T. Hosokawa, Y. Ataka, and S.-I. Murahashi, Bull. Chem. Soc. Jpn., 1990, 63, 166.

20. T. Hosokawa, F. Nakajima, S. Iwasa, and S.-I. Murahashi. Chemistry Lett., 1990, 1387.

21. J. Nokami, H. Ogawa, S. Miyamoto, T. Mandai, S. Wakabayashi, and J. Tsuji, Tetrahedron Lett., 1988, 29, 5181.

22. (a) T. Hosokawa, Y. Makabe, T. Shinohara, and S.-I. Murahashi, Chemistry Lett., 1985, 1529. (b) For related reactions, see: N. T. Byrom, R. Grigg, V. Kongkathip, G. Reimer, and A. R. Wade, J. Chem. Soc., Perkin Trans., 1984, 1, 1643; B. Kongkathip, R. Sookkho, and N. Kongkathip, Chemistry Lett., 1985, 1849.

23. K. Fugami, K. Oshima, and K. Utimoto, Tetrahedron Lett., 1987, 28, 809.

24. M. F. Semmelhack, J. J. Bozell, T. Sato, W. Wulff, E. Spiess, and A. Zask, J. Am. Chem. Soc., 1982, 104, 5850; M. F. Semmelhack and A. Zask, J. Am. Chem. Soc., 1983, 105, 2034.

25. M. F. Semmelhack and C. Bodurow, J. Am. Chem. Soc., 1984, 106, 1496; M. F. Semmelhack, C. Bodurow, and M. Baum, Tetrahedron Lett., 1984, 25, 3171; M. F. Semmelhack and N. Zhang, J. Org. Chem., 1989, 54, 4483; M. McCormick, R. Monahan III, J. Soria, D. Goldsmith, and D. Liotta, J. Org. Chem., 1989, 54, 4485; C. P. Homes and P. A. Bartlett, ibid., 1989, 54, 98.

26. Y. Tamaru, H. Higashimura, K. Naka, M. Hojo, and Z. Yoshida, Angew. Chem., Int. Ed. Engl., 1985, 24, 1045; Y. Tamaru, T. Kobayahi, S.-I. Kawamura, H. Ochiai, M. Hojo, and Z. Yoshida, Tetrahedron Lett., 1985, 26, 3207.

27. Y. Tamaru, M. Hojo, and Z. Yoshida, J. Org. Chem., 1991, 56, 1099, and references cited therein.

28. H. Alper and D. Leonard, J. Chem. Soc., Chem. Commun., 1985, 511.

29. H. Alper, Aldrich. Acta, 1991, 24, 3.

30. J. K. Stille and R. Divakaruni, J. Org. Chem., 1979, 44, 3474.

31. H. Alper and D. Leonard, Tetrahedron Lett., 1985, 26, 5639.

32. H. Alper and N. Hamel, J. Chem. Soc., Chem. Commun,, 1990, 135.

33. T. Onoda and J. Haij, Ger. Offen., 1972, 2217452 (Chem. Abstr.,1973, 78, 57786); Mitsubishi Kasei Corp., CHEMTECH, 1988, 759; see also K. Takehira, H. Mimoun, and I. S. De Roch, J. Catal., 1979, 58, 115 and references cited therein.

34. J. E. Bäckvall, Acc. Chem. Res., 1983, 16, 335; Pure & Appl. Chem., 1983, 55, 1669.

35. J. E. Bäckvall, P. G. Andersson, and J. O. Vågberg, Tetrahedron Lett., 1989, 30, 137.

36. J. E. Bäckvall and P. G. Andersson, J. Org. Chem., 1991, 56, 2274.

37. For a related reaction, see J. E. Bäckvall and P. G. Andersson, J. Am. Chem. Soc., 1990, 112, 3683.

38. J. E. Bäckvall, S. E. Byström, and R. E. Nordberg, J. Org. Chem., 1984, 49, 4619; J. E. Bäckvall, J. Vågberg, and R. E. Nordberg, Tetrahedron Lett., 1984, 25, 2717.

39. For a catalyst system using molecular oxygen; see J. E. Bäckvall, R. B. Hopkins, H. Grennberg, M. M. Mader, and A. K. Awasthi, J. Am. Chem. Soc., 1990, 112, 5160; J. E. Bäckvall, A. K. Awasthi, and Z. D. Renko, J. Am. Chem. Soc., 1987, 109, 4750.

40. (a) K. Uchimoto, Pure & Appl. Chem., 1983, 55, 1845. (b) K. Uchimoto, J. Synth. Org. Chem. Jpn., 1987, 45, 112.

41. C. Lambert, K. Uchimoto, and H. Nozaki, Tetrahedron Lett., 1984, 25, 5323.

42. (a) N. Yanagihara, C. Lambert, K. Iritani, K. Uchimoto, and H. Nozaki, J. Am. Chem. Soc., 1986, 108, 2753. (b) K. Iritani, N. Yanagihara, and K. Uchimoto, J. Org. Chem., 1986, 51, 5501.

43. M. Riediker and J. Schwartz, J. Am. Chem. Soc., 1982, 104, 5842.

44. For a related reaction; see A. Arcadi, S. Cacchi, M. Delmastro, and F. Marinella, Synlett., 1991, 409.

45. K. Kaneda, T. Uchiyama, Y. Fujiwara, T. Imanaka, and S. Teranishi, J. Org. Chem., 1979, 44, 55.

46. S. Ma and X. Lu, J. Org. Chem., 1991, 56, 5120.

47. Y. Fukuda, H. Shiragami, K. Utimoto, and H. Nozaki, J. Org. Chem., 1991, 56, 5816.

48. (a) J. R. Norton, K. E. Shenton, and J. Schwartz, Tetrahedron Lett., 1975, 51. (b) T. F. Murray, E. G. Samsel, V. Varma, and J. R. Norton, J. Am. Chem. Soc., 1981, 103, 7520. (c) For a mechanistic study; see E. G. Samsel and J. R. Norton, ibid., 1984, 106, 5505.

49. C. G. Chavdarian, S. L. Woo, R. D. Clark, and C. H. Heathcock, Tetrahedron Lett., 1976, 1769.

50. B. Despeyroux and H. Alper, Ann. N. Y. Acad. Sci., 1983, 415, 148.

51. D. Zargarian and H. Alper, Organometallics, 1991, 10, 2914.

52. R. D. Walkup and G. Park, Tetrahedron Lett., 1987, 28, 1023; see also D. Lathbury, P. Vernon, and T. Gallagher, ibid., 1986, 27, 6009.

53. L. S. Hegedus, Angew. Chem., Int. Ed. Engl., 1988, 27, 113; L. S. Hegedus, Tetrahedron, 1984, 40, 2415; L. S. Hegedus, J. Mol. Catal., 1983, 19, 201; Y. Ohshiro and T. Hirao, J. Synth. Org. Chem. Jpn., 1983, 41, 604.

54. (a) B. M. Trost, Angew. Chem., Int. Ed. Engl., 1989, 28, 1173. (b) As recent reports of palladium(0) catalyzed cyclizations; see A. Kalivrefenos, J. K. Stille, and L. S. Hegedus, J. Am. Chem. Soc., 1991, 56, 2883; R. Grigg, V. Sridharan, and S. Sukirthalingam, Tetrahedron Lett., 1991, 32, 3855; M. Iwasaki, Y. Ishii, and H. Hidai, J. Synth. Org. Chem. Jpn., 1991, 49, 909.

Received, 8th November, 1991