Mechanism of Palladium-Catalyzed Allylic Acetoxylation of Cyclohexene

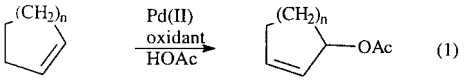
Helena Grennberg* and Jan-E. Bäckvall*

Abstract: The mechanism of the quinone-based palladium-catalyzed oxidation of cyclohexene to allylic acetate was studied under various reaction conditions with 1,2-dideuterocyclohexene (62–74% D) as the substrate. The reactions gave a 1:1 mixture of 1,2-dideutero- and 2,3-dideutero-1-acetoxy-2-cyclohexene (**2** and **3**, respectively), as determined by ^{1}H NMR spectroscopy. Control experiments with 1-deutero-1-acetoxy-2-cyclohexene showed that no 1,3-allylic transposition of the acetoxy group occurred under the reaction conditions employed for the allylic acetoxylation. These results provide evidence for a (π-allyl)palladium intermediate in the quinone-based palladium-catalyzed allylic acetoxylation. With added chloride ligands and extended reaction times, bis-allylic acetates were formed. The presence of a stoichiometric amount of CH_3SO_3H led to the formation of a homoallylic acetate.

Keywords: allylic oxidation · homogeneous catalysis · palladium · pi-allyl intermediates · isotopic labeling

Introduction

Allylic oxidation of olefins is an important reaction in organic chemistry because it leads to synthetic intermediates that can be used for further functionalizations. Direct allylic functionalization of readily available olefins has already been investigated.[1] Apart from radical-initiated reactions,[2] reactions based on selenium[3] and transition metals[4] have attracted considerable interest. Among all these methods, the quinone-based palladium-catalyzed allylic acetoxylation stands out as a practical and highly useful process for the synthesis of allylic alcohol derivatives [Eq. (1)].[5–10] In particular, simple cyclic



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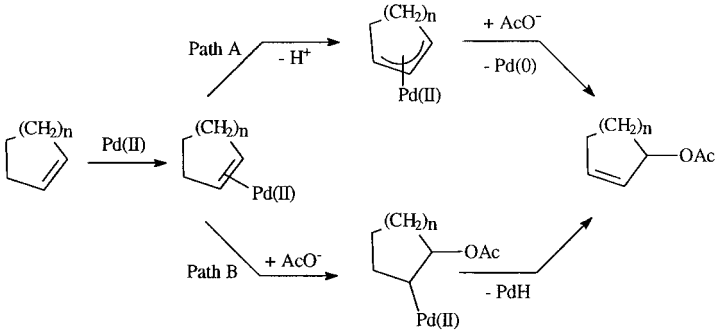
olefins are oxidized to their corresponding allylic carboxylates in excellent yields and high selectivity with *p*-benzoquinone (BQ) as a stoichiometric oxidant or electron-transfer mediator.

Two different mechanisms for this palladium-catalyzed process have been suggested.[11–14] These mechanisms involve different organometallic intermediates: a (π-allyl)palladium complex or a (σ-alkyl)palladium complex. Both pathways begin with the coordination of the alkene to Pd^{II}. The pathway of the (π-allyl) mechanism (Scheme 1, Path A) then involves the formation of a π complex, followed by the cleavage of the allylic C–H bond.[15] Subsequent nucleophilic attack by acetate[16] would then give the observed allylic acetate. The pathway of the (σ-alkyl) mechanism[11, 13] (Scheme 1, Path B) would involve attack of the olefin–palladium complex by acetate. The (σ-alkyl)palladium intermediate obtained would then undergo a β-elimination to give the observed product.



Scheme 1. The two proposed mechanisms for the palladium-catalyzed allylic acetoxylation: (π-allyl) route (A) versus the oxypalladation route (B).

The latter pathway was proposed by Winstein et al.,[12] in a study of the stoichiometric oxidation of 1- and 2-butene. The involvement of an acetoxypalladation in the catalytic oxidation of cyclohexene to complex mixtures of products with a $PdCl_2$–$CuCl_2$ oxidation system was demonstrated by Henry, although a competing (π-allyl)palladium pathway was not completely excluded.[11, 13] The (π-allyl)palladium pathway was favored by Wolfe et al.[14] based on results from the catalytic oxidation of isotopically labeled cyclohexene with a Pd^{II}–HNO_3 oxidation system, in which the main by-product was a homoallylic acetate. Frankel and co-workers also proposed a (π-allyl)palladium intermediate in the palladi-

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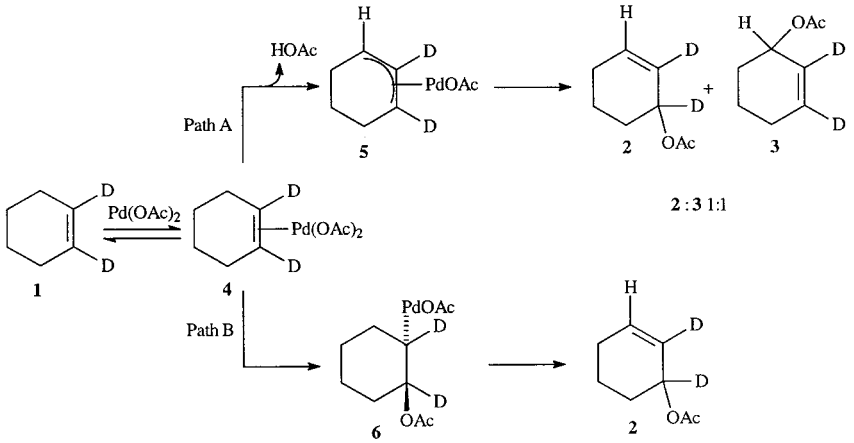
um-catalyzed oxidation of methyl oleate with $CuCl_2$ or $LiNO_3$ as stoichiometric oxidants, and various Pd catalysts, such as palladium chloride, palladium acetate, and supported zerovalent palladium.[17] Therefore, it seems that the mechanism depends upon both the substrate and the oxidation system.

The quinone-based palladium-catalyzed allylic acetoxylation has been assumed to proceed via the (π-allyl)-palladium pathway (Path A), although evidence for such a mechanism has been lacking until recently. In a preliminary communication,[18] we provided evidence for the involvement of a (π-allyl)palladium intermediate in the palladium(II)-benzoquinone-catalyzed allylic acetoxylation of cyclohexene. In the present paper, we give a full account of these results, discuss the mechanism, and also present additional results that support the (π-allyl)palladium route.



Scheme 2. Expected outcome of the (π-allyl) route (A) versus the oxypalladation route (B) in the allylic acetoxylation of 1,2 dideuterocyclohexene.

Results and Discussion

Choice and preparation of the substrate: In order to distinguish between the two possible mechanisms (Scheme 1), a substrate was required in which the position of the original double bond can be easily determined in the product.[19] Olefins such as 3- and 4-methylcyclohexene would not be useful candidates for this type of study since asymmetrical olefins have been found to yield mixtures of regioisomeric allylic acetates.[7] Although studies with the objective of improving the selectivity by the addition of ligands,[6] strong acids,[20] or different palladium–oxidant combinations[21] have been carried out, the problem of regiocontrol has not yet been solved and interpretation of the results from the oxidation of such olefins would not be unambiguous. This problem would, however, not arise for an isotopically labeled substrate such as 1,2-dideuterocyclohexene (**1**), which can form only one regioisomer of each proposed intermediate, thus minimizing the number of regioisomeric allylic acetates generated. Additionally, deuterium substituents would not affect the reaction rates as much as would carbon substituents.

Cyclohexene deuterated in the vinylic position was obtained from hexahydrophthalic anhydride by an α-proton–deuterium exchange, with D_2SO_4 or DCl as the deuterium source, followed by decarboxylation of the corresponding acid with $Pb(OAc)_4$.[22] If commercial D_2SO_4 (99.5% D) was used, then several cycles of dehydration–α-proton–deuterium exchange–hydrolysis of the hexahydrophthalic acid formed in the first step had to be performed prior to decarboxylation in order to obtain a product sufficiently enriched (>60%) in deuterium.[23]

Allylic acetoxylation: In Scheme 2, the expected outcome of an allylic acetoxylation of 1,2-dideuterocyclohexene is shown for the two pathways. In both cases, the initial step would be the formation of a π-olefin complex **4**. Then, either cleavage of an allylic C–H bond[15] to yield a (π-allyl)palladium intermediate **5**, or a *trans* attack[13, 24] by acetate to give **6** takes place. Both pathways would produce a dideuterated 1-acetoxy-2-cyclohexene[25], which is fully deuterated at C2. Assuming that the secondary isotope effect in the nucleophilic attack by acetate on the (π-allyl)palladium intermediate is negligible, the (π-allyl) pathway would give equal amounts of the products **2** and **3**. The acetoxypalladation pathway would, on the other hand, yield only the allylic acetate **2**. For an olefin containing less deuterium, the reasoning is analogous since the amount of deuterium at C2 in the product would reflect the degree of deuteration in the starting olefin.[23, 26]

The results from the allylic acetoxylation of **1** (62–74% D) are summarized in Table 1. Oxidation of **1** with $Pd(OAc)_2$ as the stoichiometric oxidant in acetic acid at room temperature afforded a 1:1 mixture of the deuterated products **2** and **3**, as determined by ^1H NMR spectroscopy[26] (entry 1). This is in excellent agreement with what is expected from a mechanism involving a (π-allyl)palladium intermediate. An increase in the temperature did not affect the outcome of the reaction (entry 2). The same result was obtained with catalytic amounts (1–5%) of $Pd(OAc)_2$ and *p*-benzoquinone (BQ) as the stoichiometric oxidant (entries 3–6 and 9). Neither the addition of LiOAc (entry 7), nor the use of Pd/C[17] (entry 10), $PdCl_2$[27] (entry 8), nor $Pd(OCOCF_3)_2$ in the presence of 2′-methoxyacetophenone as ligand[6] (entry 11) affected the ratio of compounds **2** and **3**.

Several different oxidation systems were tried in the allylic acetoxylation of **1** without any significant change in the ratio of compounds **2** and **3**. Thus, systems such as cat. $Pd(OAc)_2$/cat. BQ/MnO_2, cat. $Pd(OAc)_2$/cat. BQ/cat. iron phthalocyanine ($Fe(Pc)/O_2$) and cat. $Pd(OAc)_2/CuCl_2$ all afforded a 1:1 ratio of **2** and **3** (entries 12–16). All oxidation systems, apart from $Pd^{II}–CuCl_2$[28] and $PdCl_2$–BQ,[27] yielded clean reactions with allylic acetate as the main or only observed product. Control experiments with isolated (η^3-allyl)palladium chloride and acetate complexes[29] did verify that allylic acetate does form from such complexes in the presence of BQ, however, much more rapidly for an acetoxy complex than for a chloro complex.[30]

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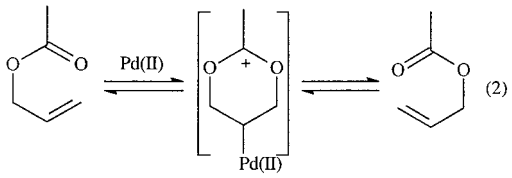
Table 1. Allylic oxidation of 1,2-dideuterocyclohexene (62–74% D).[a, b]

Entry	Pd^{II} [%]	Oxidant[d] (Additive)	T [°C] (time [h])	% D[b]	^{1}H NMR (H3:H2:H1)[c] Predicted via π-allyl[e]	Predicted acetoxypalladation[e]	Observed ratio[f]
1	$Pd(OAc)_2$ (100)	none	25 (4h45)	62	1.81:1:1.81	2.63:1:1	1.43:1:1.50
2	$Pd(OAc)_2$ (100)	none	60 (2h40)	73	2.35:1:2.35	3.70:1:1	1.64:1:1.64
3	$Pd(OAc)_2$ (1)	A	60 (26h45)	73			1.96:1:2.0
4	$Pd(OAc)_2$ (2)	A	60 (25h)	73			2.0:1:1.98
5	$Pd(OAc)_2$ (5)	A	60 (20h)	73			1.89:1:2.18
6	$Pd(OAc)_2$ (5)	A	26–28 (25h)	73			1.88:1:1.84
7	$Pd(OAc)_2$ (5)	A (0.5 M LiOAc)	60 (21h)	73			1.88:1:1.75
8	$PdCl_2$ (5)	A	60 (25h)	74	2.42:1:2.42	3.85:1:1	1.84:1[g]
9	$Pd(OAc)_2$ (5)	B	60 (20h)	73	2.35:1:2.35	3.70:1:1	1.97:1:1.79
10	10% Pd/C (3)	B	60 (6h)	62	1.81:1:1.81	2.63:1:1	1.61:1:1.7
11	$Pd(TFA)_2$ (5)	B (ligand)[h]	25 (6h)	74	2.42:1:2.42	3.85:1:1	1.57:1:1.51
12	$Pd(OAc)_2$ (0.5)	C	60 (50h)	63	1.85:1:1.85	2.72:1:1	1.88:1:1.88
13	$Pd(OAc)_2$ (1)	C	60 (45h)	70	2.17:1:2.17	3.33:1:1	2.17:1:2.08[i]
14	$Pd(OAc)_2$ (2)	C	60 (38h)	70			2.23:1:2.23
15	$Pd(OAc)_2$ (5)	D	60 (5h30)	74	2.42:1:2.42	3.85:1:1	2.04:1:2.07[i]
16	$Pd(OAc)_2$ (5)	E	50 (22h)	74			2.02:1:2.04[i]

[a] The reactions were carried out on a 0.25–0.5 mmol scale. [b] See the Experimental Section. [c] The integral of H2 of 1-acetoxy-2-cyclohexene was used to normalize the integrals of H3 and H1. See the Experimental Section. [d] A: 200% BQ and B: 100% BQ. See refs. [6, 20, and 35], C: 10% BQ and 110% MnO_2, see refs. [5] and [7], D: 10% hydroquinone, 5% Fe(Pc), st. O_2, see ref. [8a], E:10% hydroquinone, 5% $Cu(OAc)_2$, 1 atm O_2, see ref. [8b]. [e] Calculated values. [f] Estimated error ±0.02. [g] Formation of diacetate with resonance at the same chemical shift as H1. [h] 2′-Methoxyacetophenone, see ref. [6]. [i] Averaged values ($n_{exp} = 2$).

To completely verify the (π-allyl)palladium pathway in allylic oxidation, the potential involvement of a 1,3-allylic transposition of the acetoxy substituent[31] [Eq. (2)] was



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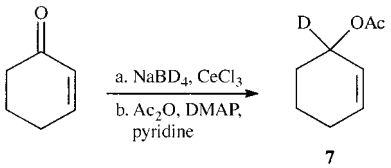
investigated. This type of rearrangement, proposed to involve a cyclic σ-palladium intermediate, would, if rapid enough, lead to the observed 1:1 ratio of allylic acetates **2** and **3** (Table 1) for the acetoxypalladation pathway too.[32]

Thus, 1-acetoxy-1-deutero-2-cyclohexene (**7**) (90% D), prepared by $CeCl_3$-catalyzed $NaBD_4$ reduction of 2-cyclohexenone[33] and subsequent esterification [Eq. (3)], was



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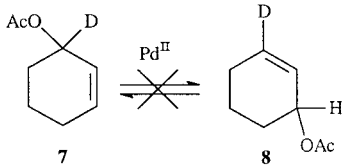
subjected to various reaction conditions. When allylic acetate **7** was treated with catalytic amounts of $Pd(OAc)_2$ (5 mol%) in the presence of excess BQ (150–200 mol%) in acetic acid at 60 °C for 16 h, no rearrangement to 1-acetoxy-3-deutero-2-cyclohexene (**8**) [Eq. (4)] could be detected by ^{1}H NMR spectroscopy (integration of H1 and H3).



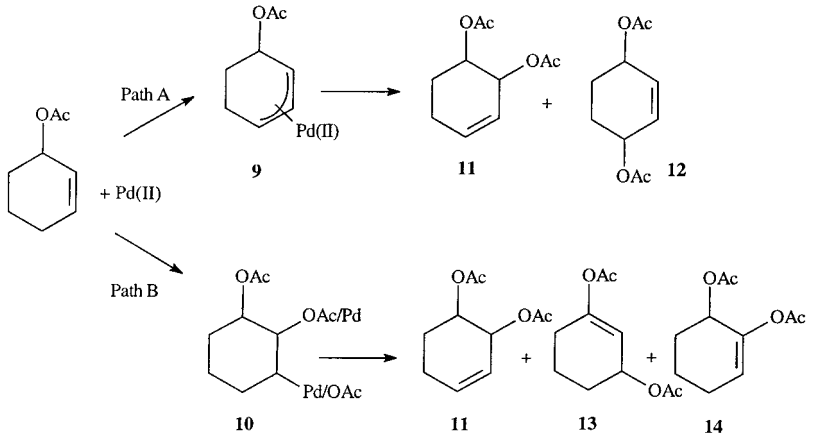
(4)

7 **8**

This was also observed in the experiments run in the presence of BQ and hydroquinone (100 mol% of each), or excess hydroquinone (150–200 mol%). In some experiments, a palladium mirror formed, without any significant effect on the distribution of deuterium in the allylic acetate. Not even the treatment of **7** with $PdCl_2(PhCN)_2$ in THF at room temperature for 2 h[31a] resulted in a rearrangement of more than 1–2%. It is most likely that longer reaction times are required for this kind of substrate.[34] Thus, even if the 1,3-allylic shift of the acetate can occur under the conditions of the allylic acetoxylation, the process is apparently not fast enough to account for the results observed for the allylic oxidation of **1** (Table 1), and therefore the acetoxypalladation pathway can be excluded.

Further oxidation of the primary product: 1-Acetoxy-2-cyclohexene, the primary product of an allylic acetoxylation of cyclohexene, is still a possible substrate for allylic acetoxylation. Thus, a second oxidation leading to diacetoxycyclohexene may occur. The regiochemistry of the diacetates that may form in the second oxidation will depend on the mechanistic pathways involved in that step.

Oxidation of 1-acetoxy-2-cyclohexene (Scheme 3) via a (π-allyl)palladium intermediate **9** (Path A) could yield 1,2-diacetoxy-3-cyclohexene (**11**) and 1,4-diacetoxy-2-cyclohexene (**12**). It is known that complex **9** only yields 1,4-substituted products in the presence of benzoquinone,[16b] thus, the bis-allylic diacetate **12** would be the only product from Path A.



Scheme 3. Oxidation of 1-acetoxy-2-cyclohexene.

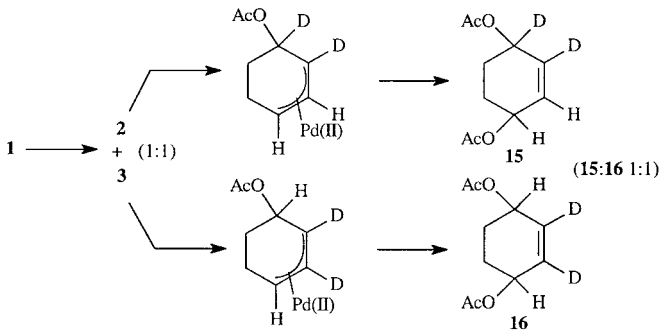
On the other hand, an oxidation involving acetoxypalladation (Path B) could yield 1,2-diacetoxy-3-cyclohexene (**11**), 1,3-diacetoxy-1-cyclohexene (**13**), and 1,2-diacetoxy-2-cyclohexene (**14**). Therefore, it is possible to determine which of the two mechanistic pathways is operating by GLC and ^{1}H NMR spectroscopic analyses of the oxidation products.[35]

When 1-acetoxy-2-cyclohexene reacted with $Pd(OAc)_2$ and BQ under allylic acetoxylation conditions, but in the presence of chloride ligands,[5, 7, 8] a slow reaction occurs in which 1,4-diacetate **12**[36] was isolated as a 1:1 mixture of *cis* and *trans* isomers, together with unreacted starting material. This is the expected outcome from a mechanism involving a (π-allyl) intermediate (Scheme 3, Path A).

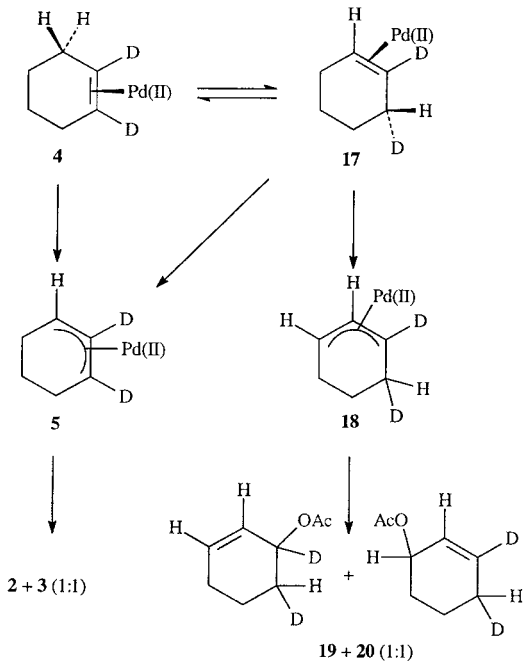
The position of the deuterium label in the diacetate obtained from **1** via secondary in situ oxidation of the allylic monoacetate (Scheme 4) was also consistent with a (π-allyl) mechanism for both oxidation steps. The predicted ^{1}H NMR integration ratio of (H1 + H4) and (H2 + H3) of 1,4-diacetoxy-2-cyclohexene (**15** + **16**) obtained from **1** (74% D) is 1.83:1 for the (π-allyl) mechanism.[26] The observed ratio of these integrals is in good agreement with this mechanism (Table 2).

Thus, the regiochemistry of the product formed in the secondary oxidation of 1-acetoxy-2-cyclohexene and the distribution of the deuterium label in the two-step oxidation of **1** provide further evidence for the involvement of (π-allyl)palladium intermediates in the palladium-catalyzed allylic acetoxylation reaction.

Isomerization of cyclohexene: In allylic acetoxylation, the rate-determining step is most likely the formation of the (π-allyl)palladium intermediate, since nucleophilic attack on (π-allyl)-palladium acetate complexes has been found to be very rapid in the presence of BQ.[16] Because of the slow allylic C–H bond cleavage, double bond isomerization[37] of the substrate olefin **1** may compete with formation of (π-allyl)palladium complex **5**. Although this isomerization has been reported to be slow,[15b, 38] it does seem to occur to a small extent since the integral ratio of H2 to H3 (Table 1) indicates a loss of deuterium at C2.[39] As mentioned above, independent of which mechanism operates in the allylic acetoxylation, there should be no loss of deuterium at C2. The slight



Scheme 4. Diallylic oxidation of cyclohexene **1** via allylic acetates **2** and **3**.



Scheme 5. Allylic acetates arising from intermediates in the rearrangement of cyclohexene **1**.

Table 2. Diallylic oxidation of 1,2-dideuterocyclohexene (74% D).[a, b]

Entry	Pd^{II} [%]	Oxidant [%]	Additive	T [°C] (time)	Oxidation product[c]	^{1}H NMR of (**15** + **16**) (H1 + H4:H2 + H3)[b, c, d, e]
1	$Pd(OAc)_2$ (5)	BQ(200)	150% LiCl	60 (26h)	(**15** + **16**)	1.62:1
2	$Pd(OAc)_2$ (5)	BQ(200)	150% LiCl	60 (26h)	(**15** + **16**)	1.54:1
3	$PdCl_2$ (5)	BQ(200)	no additive	60 (25h)	(**15** + **16**):(**2** + **3**) 1:1	1.84:1

[a] The reactions were carried out on a 0.25 mmol scale. [b] See the Experimental Section. [c] Determined by ^{1}H NMR spectroscopy of the product mixture. [d] The integrals of H2 and H3 of 1,4-diacetoxy-2-cyclohexene was used to normalize the integals of H1 and H4. [e] Acetoxypalladation + π-allyl would give an ^{1}H NMR integration ratio of $(2 - x_D)$:$(2 - x_D)$ (i.e. 1:1), whereas the corresponding ratio for π-allyl + π-allyl would be $(4 - x_D)/(4 - 3x_D)$:1 (i. e. 1.83:1 for $x_D = 0.74$).

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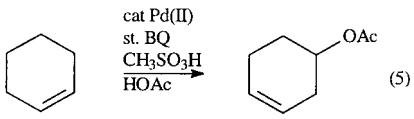
isomerization may be due to a hydride elimination–readdition mechanism, or to a reversible formation of a (π-allyl)palladium intermediate.

The relative integral of H3 in the 1-acetoxy-2-cyclohexene product should remain constant, regardless of the amount of isomerization of **4** to **17**, whereas that of H2 should increase as the amount of product from the nucleophilic attack on **18** increases (Scheme 5). The distribution of allylic acetates arising from **5** (**2** and **3**) to those from **18** (**19** and **20**) was calculated as the ratio of the observed ^{1}H NMR integral of H2 to that expected from the amount of deuterium label expected if no rearrangement of **4** to **17** had occurred.[26, 40] It was found that under standard conditions, the estimated amount of product from **18** was 5–10%, but in reactions run with a stoichiometric amount of $Pd(OAc)_2$, or with catalytic amounts of Pd/C or $Pd(OCOCF_3)_2$, it was as much as 15–20%.

Oxidation leading to the homoallylic acetate: Åkermark et al.[20] reported that reaction conditions selective for allylic acetoxylation, in the presence of a strong acid, such as CH_3SO_3H, gave good yields of homoallylic acetate [Eq. (5)].[41]



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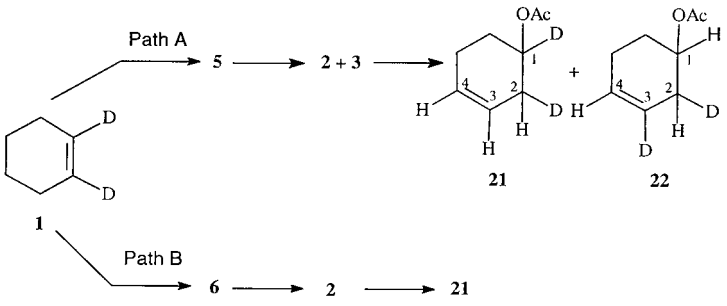
In a study of 3,3,6,6-tetradeuterocyclohexene, Wolfe and Campbell observed that small amounts of homoallylic acetates were formed in addition to the allylic acetates that constituted the major isolated products.[14] The observed position of the deuterium labels in the homoallylic acetate indicated that an acetoxypalladation–elimination–double bond migration reaction pathway might be operating parallel to the π-allyl pathway leading to the allylic product.

For 1,2-dideuterocyclohexene, such an acetoxypalladation–elimination–double bond migration sequence (Scheme 6, Path B) would lead to homoallylic acetate **21**.

In order to test this hypothesis, we subjected **1** to homoallylic oxidation conditions [Eq. (5)].[20] The 1-acetoxy-3-cyclohexene thus obtained did not show the ^{1}H NMR integral ratio expected for **21**,[26] but rather one with the deuterium label distributed over C1, C2, C3, *and* C4. The integral ratio observed agrees more closely with a mechanism involving a (π-allyl)palladium intermediate: the homoallylic acetate may form from allylic acetate in a rearrangement reaction.[42] Such a (π-allyl)-acetate attack–double bond migration pathway would yield homoallylic acetates **21** and **22** (Scheme 6, Path A).



Scheme 6. Expected outcome of the oxypalladation route (A) versus the (π-allyl) route (B) in the homoallylic acetoxylation of 1,2-dideuterocyclohexene.

When the oxidation of protic cyclohexene under homoallylic oxidation conditions was monitored by ^{1}H NMR spectroscopy, it was found that signals corresponding to a (π-allyl)palladium complex was observed prior to the appearance of any other product, and that the initally formed product (< 10 min at 60 °C) was allylic acetate. The amount of homoallylic acetate increased with time, as the signals for the allylic acetate disappeared.[43] This strong indication of a rearrangement from allylic to homoallylic acetate was verified in a separate ^{1}H NMR experiment, in which 1-acetoxy-2-cyclohexene was treated with $Pd(OAc)_2$ and CH_3SO_3H in deuterated acetic acid.

Conclusion

The quinone–palladium-catalyzed allylic acetoxylation of cyclohexene proceeds via a (π-allyl)palladium intermediate, as shown by the use of 1,2-dideuterocyclohexene as the substrate. The choice of stoichiometric oxidant, reaction temperature, and reaction time did not significantly affect the reaction pathway. Control experiments showed that no significant isomerization of the allylic acetate via 1,3-allylic transposition occurred under the normal reaction conditions for the allylic acetoxylation. These results eliminate acetoxypalladation as a possible pathway in the palladium-catalyzed allylic acetoxylation of cyclohexene. A slight olefin isomerization was observed under allylic acetoxylation conditions.

The observations presented in this paper explain, to some extent, the results previously observed in the allylic acetoxylation of substituted olefins, and could be useful for the development of new, more selective reaction conditions for allylic acyloxylation of these substrates.

Experimental Section

^{1}H NMR spectra were recorded at 300 and 400 MHz in $CDCl_3$ and [D_4]acetic acid solutions. Analytical GLC was performed on a SE54 column (25 m, 250 μm). Chemicals and solvents were from commercial sources and were used as received. Bis[cyclohexenyl(η^3-allyl)palladium] complexes were prepared according to literature procedures.[29, 44]

1-Acetoxy-1-deutero-2-cyclohexene (**7**) (90% D): This was prepared by $CeCl_3$-catalyzed $NaBD_4$ reduction of 2-cyclohexenone[33] and subsequent esterification.

1,2-Didieuterocyclohexene (**1**): Prepared from hexahydrophthalic acid as described by Åkermark et. al[22] but with commercial D_2SO_4 (99.5% D). Several cycles of dehydration–α-proton–deuterium exchange-hydrolysis of the hexahydrophthalic acid formed in the first step had to be performed prior to the decarboxylation in order to obtain a product sufficiently enriched (> 60%) in deuterium. The amount of deuterium (x_D) in the two vinylic positions was determined by ^{1}H NMR spectroscopy from the ratio of the relative integral of the vinylic signal (I_{rel}) to that of the nondeuterated compound, which is 2. Thus, x_D can be defined by [1-(I_{rel}/2)], and varies between 0 and 1, with the latter figure representing complete deuteration (i. e. 1,2-dideuterocyclohexene).

Allylic acetoxylations of 1: These reactions were carried out on a 0.25 mmol scale in acetic acid (1 mL). The reaction product was, after extractive workup[8] and removal of most of the solvent, compared with an authentic sample. The mechanism involving acetoxypalladation would give an ^{1}H NMR integration ratio of 1-acetoxy-2-cyclohexene for protons H3, H2, and H1 (at $\delta = 5.94$, 5.69 and 5.25, respectively) of $1:(1-x_D):(1-x_D)$, where x_D is the relative amount of deuterium in the vinylic position of the starting cyclohexene. For a (π-allyl)palladium mechanism, the corresponding ratio would be $0.5(2-x_D):(1-x_D):0.5(2-x_D)$.

Allylic acetoxylation of 1-acetoxy-2-cyclohexene and diallylic acetoxylations: These reactions were carried out under allylic acetoxylation conditions with either 1-acetoxy-2-cyclohexene, protic cyclohexene, or deuterated cyclohexene **1** as the substrate. The reaction products were, after extractive workup[8] and removal of most of the solvent, compared with authentic samples of 1-acetoxy-2-cyclohexene and 1,4-diacetoxy-2-cyclohexenes. In the oxidation of **1**, a mechanism involving two (π-allyl) intermediates would give an ^{1}H NMR integration ratio for protons (H1 + H4) to (H3 + H4) (at $\delta = 5.91$ (*cis*) + 5.89 (*trans*) and 5.32 (*trans*) + 5.23 (*cis*), respectively) of $0.5(4-x_D):0.5(4-3x_D)$, [i. e. $(4-x_D)/(4-3x_D):1$], whereas the corresponding ratio for a mechanism involving an acetoxypalladation–β-elimination followed by a (π-allyl) intermediate would be $(2-x_D):(2-x_D)$, (i. e. 1:1).

Isomerization of 1 during allylic acetoxylation: This was observed as a loss of deuterium at C2 in the product relative to what was expected from either mechanism. The sum of the integrals of H1, H2, and H3 had a value less than that expected from the amount of deuterium in the substrate. The observed integrals is the sum of the contributions from intermediate **5** [*A*, **2** and **3**, $I_{H2} = 1-x_D$, $I_{H3} = 0.5(2-x_D)$], and from the (π-allyl) **18** formed from the rearranged starting material [*B*, **10** and **11**, $I_{H2} = 1$ and $I_{H3} = 0.5(2-x_D)$]. Also, $A + B = 1$ (100% product), thus $A = (1 - I_{H2,\,rel})/x_D$ and $I_{H2,\,rel} = I_{H2,\,obs}\,[0.5(2-x_D)]/I_{H3,\,obs}$, since $I_{H3} = 0.5(2-x_D)$ for all values of *A* and *B*.

Homoallylic acetoxylation: This was performed as for the allylic acetoxylations with protic cyclohexene or **1** as the substrate in acetic acid or in [D_4]acetic acid, but in the presence of CH_3SO_3H (100 mol%). The reaction product was, after extractive workup[8] and removal of most of the solvent, compared with an authentic sample. For **1**, a mechanism involving acetoxypalladation and a 1,3-hydrogen shift would give a integration ratio for hydrogens 1:2:(3 + 4) (at $\delta = 5.0$, 2.4, and 5.7 + 5.6) of $(1-x_D):(2-x_D):2$, (i. e. 0.27:1.27:2 for $x_D = 0.73$). A mechanism involving a (π-allyl) intermediate would lead to a ratio of $[0.5(2-x_D)]:(2-x_D):[0.5(4-x_D)]$ (i. e. 0.63:1.27:1.63). The results are in greater accord with the latter mechanism, however with the integral for H3 + H4 smaller than expected. This is probably due to allylic acetate rearrangement.[42]

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