Synthesis of Highly Functionalized Allylic Alcohols from Vinyl Oxiranes and N-Tosylhydrazones via a Tsuji−Trost-Like “Palladium−Iodide” Catalyzed Coupling

Cooperative Iodide - Pd(0) Catalysed Coupling of Alkoxyallenes and *N*-Tosylhydrazones: a Selective Synthesis of Conjugated and Skipped Dienes

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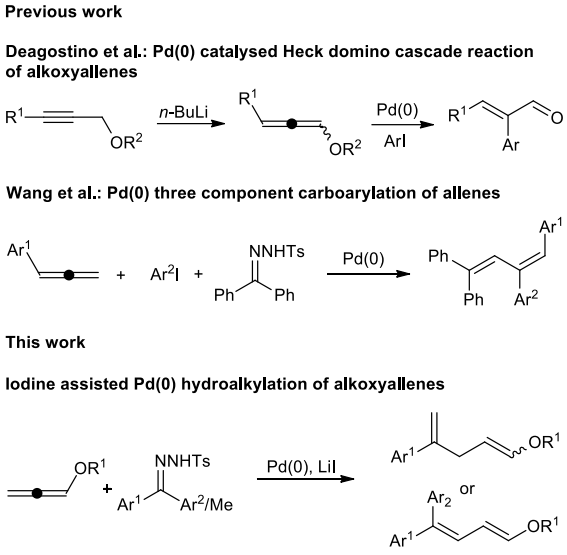
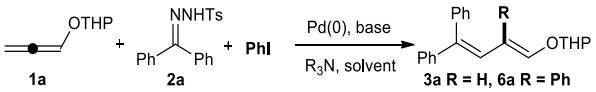
The efficient and stereoselective synthesis of dienes remains a major challenge in organic chemistry. Both 1,3-(conjugated) and 1,4-(skipped) dienes are ubiquitous structure units existing in natural products such as polyenic macrolides,[1] macrolactames,[2] alkaloids[3] and functional materials.[4] Moreover, they are key intermediates in organic synthesis given their structural and reaction properties.[5] As far as skipped dienes are concerned, the Pd(0) promoted allylic vinylation, both stoichiometric[6] and catalytic,[7] represents one of the most applied synthetic approaches.[8] More recently Ir,[9] Ni[8a, 10], Ti[11] and Cu[12] have been also exploited. Examples of the enantioselective introduction of a stereogenic centre adjacent to double bonds have been reported.[13] Another effective method is the functionalisation of 1,3 dienes catalysed by Co[14] or Pd again.[15] In the same way, the stereodefined construction of functionalised conjugated dienes represents a major goal in organic synthesis,[4a, 5a, 5b, 16] and many efforts have been devoted in the past decades exploiting metal catalysed couplings of alkynes or allenes and suitable alkenes[17] or 1,4 elimination processes.[18] Nevertheless, great attention is still paid to their preparation.[17a-c] Domino allylic alkylation/4π-electrocyclic ring opening,[1c, 19] ring closing metathesis,[20] allene-Claisen rearrangement[21] and Pd catalysed coupling of allenes and boronic derivatives[17d] were lately reported. In our laboratory we have been studying 1,2-alkoxydiene reactivity in Heck reactions and α-arylated-α,β-enals (Scheme 1),[22] dihydrobenzofurans and indolidines[23] have been prepared in a cascade domino process. Alkoxyallenes ease of synthesis and exceptional reactivity make them unusual and versatile building blocks.[24] Recently, interesting Pd catalysed functionalisation of alkoxyallenes have been developed.[25] In our procedures allenes were prepared *via* the isomerisation of internal alkynes promoted by *n*-butyllithium, not compatible with electrophilic moieties. In this context terminal allenes represent an appealing alternative, since mild isomerisation conditions are required on propynol ethers.[26] For this reason, we envisaged *N*-tosylhydrazones as ideal nucleophilic partners in a Pd(0) catalysed reaction, due the requirement for an additional carbon atom to assembly a butadiene. Our hypothesis was supported by a publication describing the synthesis of highly arylated butadienes by a three component coupling between aryl iodides, tosylhydrazones or diazo esters and propadienyl arenes (Scheme 1).[27] *N*-tosylhydrazone role in Pd(0) cross couplings is well established[28] especially thanks to the pioneering work of Barluenga and Valdés[29] and Wang.[27, 30] Examples of dienes obtained *via* Pd(0) catalysed reactions of *N*-tosylhydrazones have been reported.[31]



Scheme 1 Pd(0) catalysed reactions of alkoxyallenes, diazo compounds and allenes previously reported and the synthesis of skipped and conjugated dienes by reaction of alkoxyallenes and *N*-tosylhydrazones.

With the goal in mind of testing alkoxyallene reactivity in a three component coupling with tosylhydrazones and aryl halides, we set up a reaction with iodobenzene, alkoxyallene **1a** and benzophenone tosylhydrazone **2a**. Unfortunately, due to the alkoxy group influence on the allene electronic properties, it was not possible to promote a multicomponent process and the desired 1-alkoxy-1,3-diene **6a** was afforded in low yield together with many side products virtually impossible to separate. Nevertheless, one of those side products was easily isolated and characterised. Surprisingly the alkoxydiene **3a** was recovered, which was clearly the product of a coupling between alcoxyallene **1a** and tosylhydrazone **2a** competing with the planned three component reaction (scheme 2). Diene **3a** came from the allene hydroalkylation and was formed in a total *E* stereoselective fashion, as confirmed by NMR-NOESY (see ESI).



Scheme 2 Pd(0) catalysed coupling of alkoxyallene **1a** and benzophenone *N*-tosylhydrazone **2a**.

Encouraged by the initial result, we searched for the optimal conditions. First, iodobenzene was excluded, but surprisingly only traces of diene **3a** were recovered. We hypothesised that the aryl iodide might be needed to sustain the catalytic cycle, which was confirmed by the yield increasing with catalytic loading of PhI (5% mol, see ESI for complete screening). Triethylamine is essential as well since other tertiary amines, like DIPEA, are completely inefficient. Moreover, a 10:1 ratio with THF is ideal (see ESI). Following up, the remaining conditions were optimised, results are summarised in Table 1.

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Table 1. Optimisation of Pd(0) catalysed coupling of alkoxyallene **1a** and benzophenone *N*-tosylhydrazone **2a**.[a]

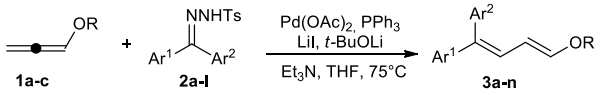
Entry	Iodide	2a (eq), Base (eq)	Catalyst	Yield [%][b]
1	PhI	1.2, *t*-BuOLi 1.2	$Pd(OAc)_2$, P(*o*-tol)$_3$	49[c]
2	PhI	**1.0, *t*-BuOLi 1.0**	$Pd(OAc)_2$, P(*o*-tol)$_3$	41[c]
3	PhI	1.2, ***t*-BuONa 1.2**	$Pd(OAc)_2$, P(*o*-tol)$_3$	0[c]
4	PhI	1.2, **K_2CO_3 1.2**	$Pd(OAc)_2$, P(*o*-tol)$_3$	0[c]
5	PhI	1.2, ***t*-BuOLi 2.4**	$Pd(OAc)_2$, P(*o*-tol)$_3$	trace[c]
6	PhI	1.2, *t*-BuOLi 1.2	**$Pd(OAc)_2$**	0[c]
7	PhI	1.2, *t*-BuOLi 1.2	**$Pd(OAc)_2$,Xphos**	trace[c]
8	PhI	1.2, *t*-BuOLi 1.2	**$Pd(OAc)_2$,DMPP**	7[c]
9	PhI	1.2, *t*-BuOLi 1.2	**$Pd(OAc)_2$,PPh_3**	80[c]
10	PhI	1.2, *t*-BuOLi 1.2	**$PdCl_2$, P(*o*-tol)$_3$**	47[c]
11	PhI	1.2, *t*-BuOLi 1.2	**$PdCl_2$·(MeCN)$_2$,P(*o*-tol)$_3$**	45[c]
12	**TBAI**	1.2, *t*-BuOLi 1.2	$Pd(OAc)_2$,PPh_3	39
13	**LiI**	1.2, *t*-BuOLi 1.2	$Pd(OAc)_2$,PPh_3	85
14	LiI	1.2, *t*-BuOLi 1.2	$Pd(OAc)_2$,PPh_3	37[d]
15	LiI	1.2, *t*-BuOLi 1.2	$Pd(OAc)_2$,PPh_3	0[e]

[a] Reactions conditions: alkoxyallene **1a** 0.5 mmol, dry THF 5 mL, Et_3N 0.5 mL, Iodide source (5% mol), Pd cat. (5% mol), Phosphine (15% mol), T = 75°C. [b] Determined on isolated product. [c] Negligible amount of **3a'** is detected. [d] Reaction carried out in toluene. [e] Reaction carried out in acetonitrile.

The initial conditions were almost optimal, considering that THF and *t*-BuOLi gave the best result. Both *t*-BuONa and K_2CO_3 (entries 3-4), which are usually effective as well, were completely inefficient in this case. We believe that this sharp difference was due to Li^+ ability to keep the iodide counterion in solution (NaI is slightly soluble in THF while KI is completely not soluble). An excess of tosylhydrazone **2a** respect to alkoxyallene **1a** was required (entries 1-2) but equimolar to *t*-BuOLi (entry 5). Different catalysts were tested (entry 6-11) and we were pleased to observe a huge improvement with PPh_3 (entry 9).

Finally, we realised that PhI was only required as iodide (I^-) source. This hypothesis was actually confirmed by replacing it with tetrabutylammonium iodide (entry 12) or lithium iodide (entry 13), with the last giving an optimal 85% yield. PhI and LiI have similar efficacy in feeding iodide to the catalyst with the former always affording an unavoidable amount of the diene **3a'** which does not affect **3a** yield anyway. Still, toluene and acetonitrile were tested without any improvement (entries14 and 15). It must be noticed that THF is rarely employed in Pd(0) couplings with *N*-tosylhydrazones. Nevertheless, it is known for its ability in stabilising electronpoor Pd(II) complexes and moreover it gives a homogeneous solution, preventing LiI precipitation and the consequent reaction failure. We chose the conditions reported in entry 13 of Table 1 for studying the reaction scope. Different benzophenones were converted in tosylhydrazones and then coupled with terminal alkoxyallenes to generate diarylated 1-alkoxy-1,3-dienes (**3a-n**) in good yield and stereoselective manner; results are listed in Table 2.

Table 2.Pd(0) coupling of alkoxyallenes (**1a-c**) and *N*-tosylhydrazones (**2a-l**) to afford 4,4'-diaryl-1-alkoxybuta-1,3-dienes (**3a-n**).[a]



1a-c **2a-l** **3a-n**

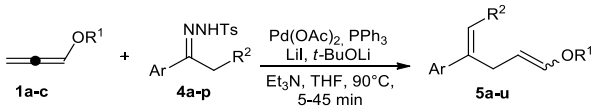
Entry	R	Ar^1	Ar^2	Yield[%][b]	*E*/*Z* (C_3-C_4)[d]
1	THP	Ph	Ph	**3a**, 85	-
2	THP	4-Tol	4-Tol	**3b**, 65	-
3	THP	4-MeOPh	4-MeOPh	**3c**, 47	-
4	THP	4-FPh	4-FPh	**3d**, 89	-
5	THP	4-PhOPh	4-PhOPh	**3e** 55	-
6	THP	4-ClPh	4-ClPh	**3f**, 81	-
7	THP	3-NO_2Ph	3-NO_2Ph	**3g**, 45	-
8	THP	Ph	4-ClPh	**3h**, 88	55/45
9	THP	Ph	2-ClPh	**3i**, 88	50/50
10	THP	Ph	3-CF_3Ph	**3j**, 85	66/33
11	THP	Ph	4-CN	**3k**, 90	70/30
12	THP	Ph	2-Tol	**3l**, 65	50/50
13	Bn	Ph	Ph	**3m**, 92	-
14	MEM	Ph	Ph	**3n**, 87	-
15	THP	Ph	Ph	**3a**, 73[c]	-

[a] Reaction conditions: alkoxyallene 0.5 mmol, *N*-tosylhydrazone (1.2 eq), *t*-BuOLi (1.2 eq), dry THF, 5 mL, Et_3N 0.5 mL, LiI (5% mol), $Pd(OAc)_2$ (5% mol), PPh_3 (15% mol). [b] Determined on isolated product. [c] Reaction scaled up to 5 mmol. [d] E/Z ratio determined by ^1H NMR on the crude.

Both electron withdrawing (entries 4-11) and -donating (entries 1-3, 12) groups are tolerated on the phenyl ring. Better results are obtained with the formers, with 3,3'-NO_2 as exception. Asymmetric *N*-tosylhydrazones afforded dienes **3h**-**l** (entries 8-12) in excellent yields. The reaction can also be performed on differently substituted allenes, with benzyl group giving a purer crude (entry 13). A tenfold scale-up successfully afforded 1.12 g of diene **3a** in a single batch.

Lately, we extended the substrate scope to arylalkyl-*N*-tosylhydrazones **4a-p**. The experimental conditions applied to diaryl-*N*-tosylhydrazones **2a-l** were not optimal, so we looked for better ones, focusing our attention on temperature and allene protecting group. The coupling was sensitive to the former, with a higher temperature (90°C) as the best value. On the contrary, the allene protecting group did not have any influence, but we choose the benzylated allene **1c** for studying the coupling scope, given benzyl group resilience compared to THP. With these derivatives we were conscious of the possible issue with the selectivity in the β hydrogen abstraction since the presence of two hydrides prone to elimination. Nevertheless, we were delighted to observe a complete regioselectivity towards skipped dienes, kinetically favoured. With these tailored conditions, a library of 1,4-dienes was prepared (Table 3).

Table 3.Pd(0) coupling of alkoxyallenes (**1a-c**) and *N*-tosylhydrazones (**4a-p**) to afford 4-aryl-1-alkoxypenta-1,4-dienes(**5a-u**).[a]



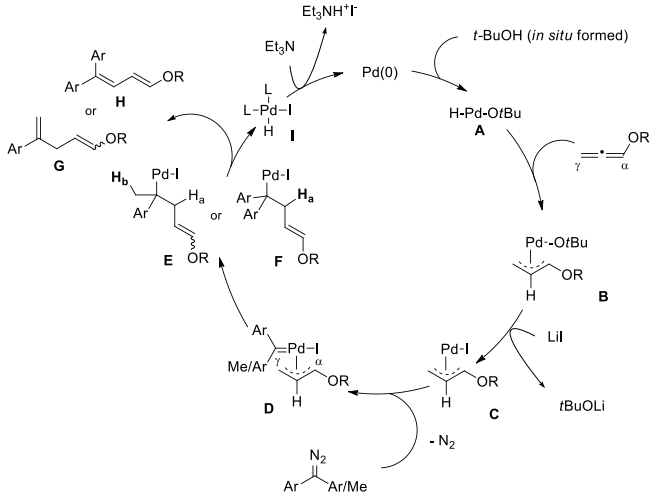
1a-c **4a-p** **5a-u**

Entry	R^1	Ar	R^2	Yield[%][b]	*E*/*Z*[c]
1[c]	Bn	Ph	H	**5a** 85,	84/16
2	Bn	2-Tol	H	**5b** 47	81/19
3	Bn	3-Tol	H	**5c**, 73,	84/16
4	Bn	4-Tol	H	**5d** 94	87/13
5	Bn	4-MeOPh	H	**5e** 52	81/19
6	Bn	2-BrPh	H	**5f** 78,	78/22
7	Bn	3-BrPh	H	**5g** 84,	78/22
8	Bn	4-BrPh	H	**5h** 60	80/20
9	Bn	4-ClPh	H	**5i** 54	77/23
10	Bn	2-CF_3Ph	H	**5j** 70	77/23
11	Bn	4-CNPh	H	**5k** 73	72/28
12	Bn	Ph	Me	**5l** 72	84/16
13	Bn	4-Py	H	**5m** 67	77/23
14	Bn	2-Thienyl	H	**5n** 55	84/16
15	Bn	2-Naphtyl	H	**5o** 77	80/20
16	THP	Ph	H	**5p** 94	81/19
17	THP	3-BrPh	H	**5q** 78	75/25
18	THP	4-CNPh	H	**5r** 80	74/26
19	MEM	Ph	H	**5s** 79	85/15
20	MEM	4-CNPh	H	**5t** 75	75/25
21	Bn	4-ethinylPh	H	**5u** 64	82/18

[a] Reactions conditions: alkoxyallene 0.5 mmol, *N*-tosylhydrazone (1.2 eq), *t*-BuOLi (1.2 eq), dry THF, 5 mL, Et_3N 0.5 mL, LiI (5% mol), $Pd(OAc)_2$ (5% mol), PPh_3 (15% mol). [b] Determined on isolated product. [c] *E*/*Z* ratio determined by ^1H NMR and GC on the crude.

Also in this case, the influence of the substituents on the aromatic ring and of the allene protecting group was explored. Results are in accordance with those listed in Table 2 for tosylhydrazones **2a-l** and good yields were obtained with both electron donating (entries 1-5) and -withdrawing moieties (entries 6-11). Sterically hindered naphtyl group is also effective (entry 15), like propiophenone tosylhydrazone (entry 12)[32]. The reaction tolerates arylbromides and chlorides, differently from aryl iodides which probably undergo oxidative addition. Electronpoor and -rich heteroarenes (entry 13 and 14 respectively) were tested with good outcomes. Moreover, thanks to the very short reaction time, this coupling is compatible with acetylenes without producing any pyrazole coming from the [3+2] dipolar cycloaddition (entry 21).[33] Finally the reaction was extended to differently protected alkoxyallenes (**1b-c**) without any remarkable changes respect to

benzyl group (entries 16-20). In all cases isomer *E* was predominant with the *E*/*Z* ratio determined by ^{1}H NMR and GC. Traces of the regioisomer deriving from the carbene α-addition were in some cases detected (see ESI). A plausible mechanism is depicted in Scheme 3.



Scheme 3 Mechanism proposal

The key step of the overall process is the generation of the allyl Pd(II) complex **B** by regioselective hydropalladation of the alkoxyallene. Then, the carbenoid **D** is formed *via* nitrogen loss from the diazo compound promoted by its interaction with the metal centre. The subsequent migratory insertion into the Pd-C bond of the η^1-allyl complex affords the alkyl Pd species **E** or **F,** depending on the tosylhydrazone. The final diene **H** or **G** is released upon *syn* abstraction of one β hydride. Iodide is necessary, in our opinion, to regenerate the active Pd(0) catalyst from the Pd hydride **I** by reductive elimination of one equivalent of HI, neutralised by Et_3N. In a normal Heck protocol, iodide is present due to the oxidative addition on the halogenated partner, while in this reaction an extra source is needed in order to sustain the catalytic cycle. It is not clear yet when iodide coordinates the Pd atom, we believe that is after the hydropalladation step to generate the intermediate **C**. The most peculiar feature of this reaction is the initial hydropalladation which requires the generation of Pd hydride at the very beginning of the catalytic cycle. At this stage, only tosylhydrazone NH proton is available, which is taken by the base to generate *t*-butanol. At the moment, we believe that the catalytic cycle starts with the oxidative addition of a Pd(0) complex into the OH group of the *in situ* formed alcohol. This process has been already described, in similar conditions, also with tertiary alcohols in THF.[34] Preliminary tests indicate that this hypothesis might be correct (see ESI). Firstly, when the reaction was run on the pre-formed tosylhydrazone lithium salt (**2aLi**) in the absence of *t*-BuOLi, the yield dropped from 85 to 13%. Secondly, when the required proton was added directly as *t*-butanol a yield increase up to 45% was noticed. Finally, the model reaction carried out reacting either *t*-BuOD or *D*-tosylhydrazone **2a(D)** with alcoxyallene **1a** showed the formation of *D*-labelled diene **3a(D),** where a little amount of deuteropalladation of sp C of allene **1a** is observed. Actually, a mixture of dienes **3a** and **3a(D)** was observed in the ^{1}H NMR (see scheme 1 and figure 2 in ESI), with a high ratio **3a**/**3a(D)** which suggests that more than one proton source is present in the reaction milieu. At the beginning it is only the tosylhydrazone **2a(D),** which explains D-incorporation in the product. Then the catalytic cycle itself might sustain the reaction, *via* an active role of triethylammonium iodide coming from HI neutralisation. Deeper investigations are ongoing to elucidate the mechanism.

In conclusion, we have developed a new method for the selective synthesis of functionalised conjugated and skipped dienes in high yield. Iodide is essential to the active Pd(0) species regeneration. Moreover, the catalytic cycle seems to start with a not common oxidative addition of Pd(0) into the hydroxyl group of the *in situ* formed *t*-BuOH.

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Keywords: Tosylhydrazones • Alkoxyallenes • Palladium • Iodide • Dienes

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