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Stereoselective Rh-Catalyzed Hydrogenative Desymmetrization of Achiral Substituted 1,4-Dienes

Héctor Fernández-Pérez,[†,§] Joan R. Lao,[†,§] and Anton Vidal-Ferran*[,†,‡,§]

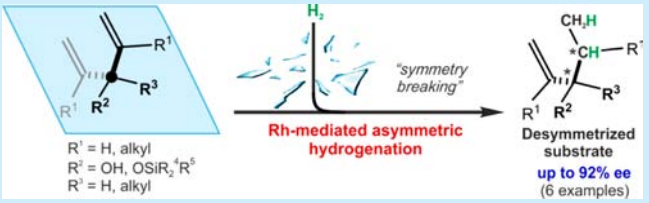
[†]Institute of Chemical Research of Catalonia (ICIQ), Av Països Catalans, 16, 43007 Tarragona, Spain

[‡]Catalan Institution for Research and Advanced Studies (ICREA), P. Lluís Companys, 23, 08010 Barcelona, Spain

[§]The Barcelona Institute of Science and Technology, Av Països Catalans, 16, 43007 Tarragona, Spain

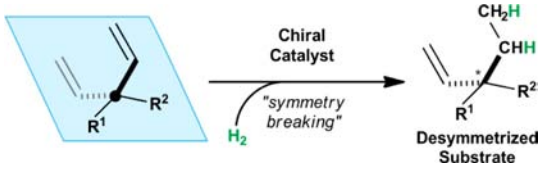
Supporting Information

ABSTRACT: Highly efficient catalytic stereoselective hydrogenative desymmetrization reactions mediated by rhodium complexes derived from enantiopure phosphine−phosphite (P−OP) ligands are described. The highest performing ligand, which contains a TADDOL-derived phosphite fragment [TADDOL = (2,2-dimethyl-1,3-dioxolane-4,5-diyl)bis(diphenylmethanol)], presented excellent catalytic properties for the desymmetrization of a set of achiral 1,4-dienes, providing access to the selective formation of a variety of enantioenriched secondary and tertiary alcohols (six examples, up to 92% ee).



The stereoselective desymmetrization of achiral and *meso* compounds has proved to be a powerful synthetic entry for the preparation of more elaborate optically enriched molecules.[1] This transformation implies breaking the symmetry of the molecule by a synthetic operation, in which two enantiotopic groups of an achiral or *meso* compound are differentiated: the choice of one enantiotopic group (or face) over the other is provided by a chiral reagent or an enantioselective catalyst. Compared to other asymmetric catalytic methodologies, desymmetrization offers several advantages,[2] such as allowing the concurrent generation of multiple stereogenic centers in a single synthetic step.[3] The potential of this synthetic method has been demonstrated by its application in a wide range of catalytic asymmetric transformations.[1] However, catalytic stereoselective desymmetrizations by reductive methods have been less studied,[1c] and for certain transformations, no satisfactory solution in terms of efficiency or chemo- and stereoselectivity has yet been developed.[4] For instance, the catalytic hydrogenative desymmetrization of achiral 1,4-dienes (Scheme 1) can be considered an example of understudied desymmetrization. Several challenges need to be addressed when developing efficient stereoselective catalysts for this transformation: (i) selectivity control in terms of obtaining the monohydrogenation product of the achiral 1,4-diene and (ii) the ability of the catalyst to differentiate two enantiotopic vinyl groups. Notable progress in this topic was made by Brown et al., who paved the way for desymmetrizing a set of achiral 1,4-dienes through enantioselective hydrogenation. These authors used enantiopure Rh bisphosphine complexes as catalysts and demonstrated the feasibility of this hydrogenative desymmetrization, though without complete control of the chemoselectivity of the reaction and with only moderate enantioselectivities (up to 53% ee).[5]

Scheme 1. Stereoselective Hydrogenative Desymmetrization of a General Achiral 1,4-Diene



Following our efforts in developing highly efficient catalytic systems derived from phosphine−phosphite (P−OP) ligands for asymmetric hydrogenations[6] and kinetic resolutions,[6k] we became interested in developing enantioselective catalysts for the hydrogenative desymmetrization of achiral 1,4-dienes (Tables 1 and 3), as the resulting products can be considered versatile building blocks for the construction of more complex molecules. Herein, we describe the optimization studies toward the identification of the lead enantioselective catalyst and development of optimal reaction conditions, together with their application in the desymmetrization of a set of structurally diverse achiral 1,4-dienes.

Compounds **1a−c** were selected for the initial studies, as these substrates had already been hydrogenatively desymmetrized by Brown et al.[5] After some experimentation, efficient desymmetrization conditions involving low temperature (−40 °C), 1 bar of H_2 in CH_2Cl_2, and the Rh complex derived from ligand **L1** as the catalyst were identified (Table 1).[7]

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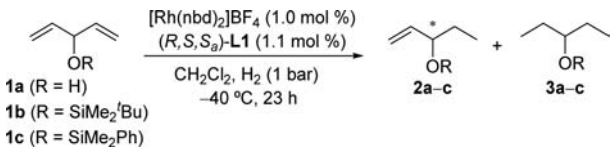
Table 1. Preliminary Studies of the Desymmetrization of Substrates 1a−c[a]



entry	substrate	conv[b] (%)	2:3[b]	ee of 2 (%)[c] (*S*)[d]
1	**1a**	>99	>99:1	46
2	**1b**	>99	>99:1	62
3	**1c**	>99	>99:1	66

[a][Substrate] = 0.1 M. [b]Determined by ^{1}H NMR. [c]Determined by chiral HPLC analysis after derivatization into the corresponding benzoyl derivatives **4**.[8] [d]The absolute configuration of **2a** was established by comparison with reported optical rotation values for **4a**. The absolute configuration of **2b** and **2c** was tentatively assigned by analogy with the stereochemical outcome of the reaction leading to **2a**.

As summarized in Table 1, the rhodium complex derived from ligand **L1** afforded products **2a−c** with full conversion and perfect chemoselectivity (**2**:**3** ratio >99:1) in the three substrates assessed (entries 1−3, Table 1). Moreover, products **2a−c** were obtained with moderate ee values (from 46 to 66% of ee; entries 1−3, Table 1). The best result in this screening was achieved for substrate **1c**, where the desymmetrized product **2c** was selectively obtained with complete conversion and with 66% ee (entry 3, Table 1). Further studies were aimed at improving the enantioselectivity of the desymmetrization of **1c** by screening a library of structurally diverse P−OP ligands (Figure 1).[9] The assayed conditions and results are listed in

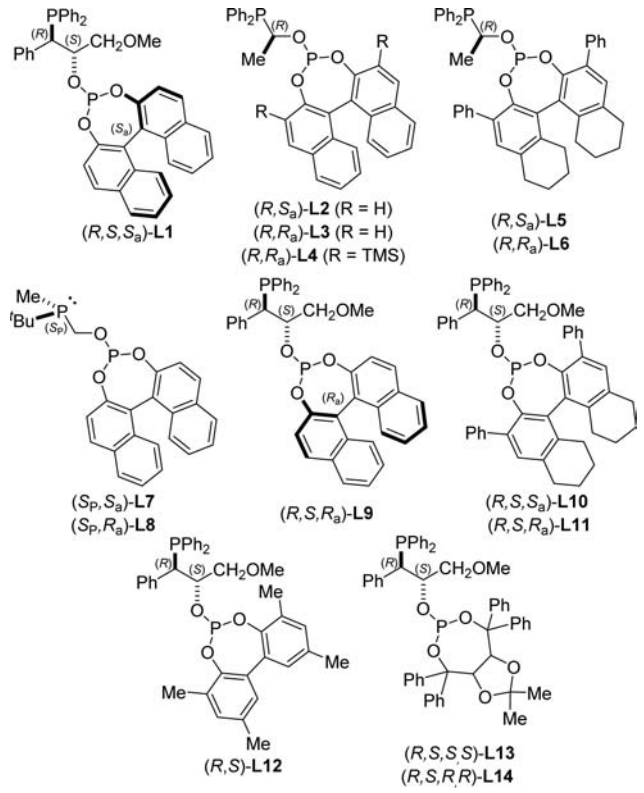
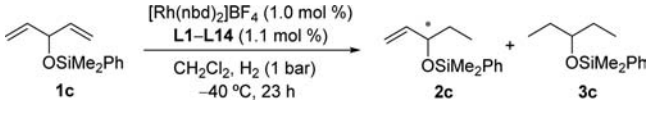


Figure 1. Library of P−OP ligands screened in the hydrogenative desymmetrization of substrate **1c**.

Table 2. Ligand Screening for Substrate 1c[a,b]



entry	ligand	2c:3c[a]	ee of 2c (%)[a] (config)[a]
1	**L2**	>99:1	*rac*
2	**L3**	>99:1	*rac*
3	**L4**	>99:1	17 (*R*)
4	**L5**	>99:1	16 (*S*)
5	**L6**	>99:1	27 (*R*)
6	**L7**	>99:1	33 (*S*)
7	**L8**	>99:1	34 (*S*)
8[c]	**L9**	>99:1	18 (*S*)
9[d]	**L1**	>99:1	66 (*S*)
10	**L10**	>99:1	36 (*S*)
11	**L11**	>99:1	33 (*R*)
12	**L12**	>99:1	49 (*S*)
13	**L13**	>99:1	80 (*S*)
14	**L14**	>99:1	77 (*S*)

[a]See footnotes *a*−*d* in Table 1. [b]Full conversion was achieved, unless otherwise stated. [c]74% of conversion was obtained. [d]This result has been already shown in Table 1.

Table 2. In general, and regardless of the nature of the set of P−OP ligands tested in these screening studies (**L1−L14**; Figure 1), their derived Rh catalysts efficiently mediated the desymmetrization of **1c** with excellent values of activity (from 74 to 99% of conversion), perfect chemoselectivity (**2c**:**3c** ratios >99:1), and variable enantioselectivities, which strongly depended on the type of ligand used (see entries 1−14; Table 2). In a first series of experiments, geminal P−OP ligands **L2−L8** (Figure 1) were tested. These narrow bite-angle ligands[9] proved to be effective in the desymmetrization of **1c** in terms of activity (conversion >99%) and chemoselectivity (**2c**:**3c** ratio >99:1), but not in terms of enantioselectivity (from null to 34% ee, entries 1−7, Table 2). Vicinal P−OP ligands[9] **L1** and **L9−L14** were subsequently studied (Figure 1). The phosphite group in the ligand played a crucial role in the enantioselectivity of the reaction. As regards P−OP ligands with [1,1′-biaryl]-2,2′-diol-derived phosphite groups (i.e., **L1** and **L9−L12**), as already discussed, ligand **L1** containing a (S_a)-BINOL-derived phosphite fragment mediated the desymmetrization of **1c** with moderately high ee (66% ee, entry 3 in Table 1). An inversion of the configuration of the phosphite fragment (ligand **L9** with a (R_a)-BINOL group) was detrimental both for the catalytic activity and enantioselectivity (74% of conversion and 18% ee; entry 8, Table 2). Ligands bearing substituents at the 3 and 3′ positions of the [1,1′-biaryl]-2,2′-diol unit (**L10** and **L11**; Figure 1) were also assessed in the desymmetrization of **1c**. Although complete conversions and chemoselectivities were observed with ligands **L10** and **L11** (entries 10 and 11; Table 2), no improvement on enantioselectivity was achieved with this modification in the ligand backbone (up to 36% ee; entries 10 and 11, Table 2). Ligand **L12**, which incorporates the 3,3′,5,5′-tetramethyl-[1,1′-biphenyl]-2,2′-diol-derived phosphite group, was also assessed in this transformation in order to study whether a conformationally adaptive biaryl group could be beneficial for the stereoselectivity of the reaction. As with the other ligands studied, this new ligand mediated the desymmetrization of **1c** with perfect conversion and chemoselectivity but moderated enantioselectivity (49% ee; entry 12,

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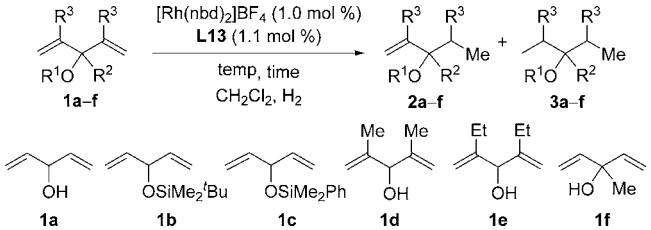
Table 2). In order to broaden the structural diversity of the catalyst, ligands containing the TADDOL-derived phosphite fragment [TADDOL = (2,2-dimethyl-1,3-dioxolane-4,5-diyl)-bis(diphenylmethanol)] were included in this study (**L13** and **L14**; Figure 1).[11,12] The use of these ligands in the desymmetrization of **1c** resulted in a considerable improvement in the enantioselectivities of **2c** (ranging from 77 to 80% ee; entries 13 and 14, Table 2) compared to the other ligands assessed in this study (Table 2). Interestingly, the sense of stereoinduction in the desymmetrization of **1c** mediated by **L13** and **L14** is mainly dictated by the stereocenters of the ligand backbone, as the (*S*,*S*)- and (*R*,*R*)-TADDOL-containing ligands (**L13** and **L14**, respectively) led to product **2c** having the same absolute configuration.

With an optimal catalyst for desymmetrizing **1c** in hand, the desymmetrization of **1a** and **1b** with the optimal TADDOL-containing ligand **L13** was then studied. The substrate scope of the reaction was also expanded to structurally diverse 1,4-dienes **1d**–**f** using the optimal ligand **L13**. The optimized reaction conditions and the best results obtained in this study are listed in Table 3. Substrate **1a** and its *O*-silylated analogue **1b** were

Table 3. Substrate Scope for the Desymmetrization of Substrates 1a–f[a,b]

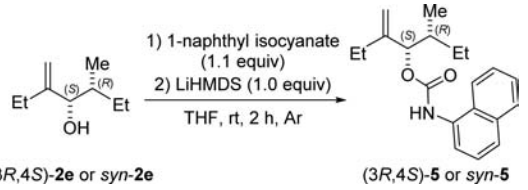


entry	substrate	*P* (bar)	temp (°C)	time	2:3[a]	ee of **2** (%)[a] (config)[a,c]
1	**1a**	1	−40	23 h	>99:1	84 (*S*)
2[d]	**1b**	1	−40	23 h	>99:1	87 (*S*)
3[e]	**1c**	1	−40	23 h	>99:1	80 (*S*)
4	**1d**	5	−20	5 d	>98:2	59 (*S*)
5	**1e**	5	−20	5 d	>92:8[f]	70 (3*R*,4*S*)
6	**1f**	1	−40	23 h	>99:1	92 (*S*)

[a]See footnotes *a*–*d* in Table 1. [b]Full conversion was achieved, unless otherwise stated. [c]The absolute configuration of products **2d**–**f** was tentatively assigned by analogy with the stereochemical outcome of the reaction leading to **2a**. [d]64% of conversion was obtained. [e]This result has been shown in Table 2. [f]dr of *syn*-**2e** > 99:1, as determined by ^{1}H NMR.[10]

efficiently desymmetrized by the Rh catalyst derived from **L13** with perfect chemoselectivities (**2**:**3** ratio >99:1) and with high enantioselectivities (84 and 87% ee; entries 1 and 2 in Table 3). Switching from a hydroxyl group (in **1a**) to bulkier silyl ether groups (in **1b** and **1c**) was well tolerated by the catalyst and did not greatly affect the outcome of the reaction in terms of chemo- and enantioselectivity. Substrates **1d** and **1e** were studied in order to assess the influence of substituents at the 2 and 4 positions of the 1,4-diene. The presence of these substituents made necessary the use of higher H_2 pressure (5 bar instead of 1 bar of H_2), higher temperatures (−20 °C instead of −40 °C), and extended reaction times (5 days instead of 23 h). Enantioselectivities of the desymmetrized products **2d** and **2e** were lower (59 and 70% ee, respectively; entries 4 and 5, Table 3) than those observed for the unsubstituted products **1a**–**c** (compare entries 4 and 5 with

Scheme 2. Derivatization of Product *syn*-2e to 5[10]



entries 1–3 and 6; Table 3). Interestingly, a slight increase in the bulkiness of the substituents at the 2 and 4 positions (from methyl in **1d** to ethyl in **1e**) translated into an increase in the enantioselectivity of up to 11% (from 59 to 70% of ee; compare entries 4 and 5, Table 3). Furthermore, the desymmetrization of **1e** led exclusively to the formation of the *syn*-**2e** diastereoisomer (dr or *syn*:*anti* ratio >99:1; entry 5, Table 3).[10,13] Derivatization of the reaction product *syn*-**2e** into the 1-naphthylurethane derivative **5** (Scheme 2) was efficiently performed, and the relative stereochemistry of product *syn*-**2e** was unequivocally established from the crystalline derivative **5** by single-crystal X-ray analysis (Figure 2).[10]

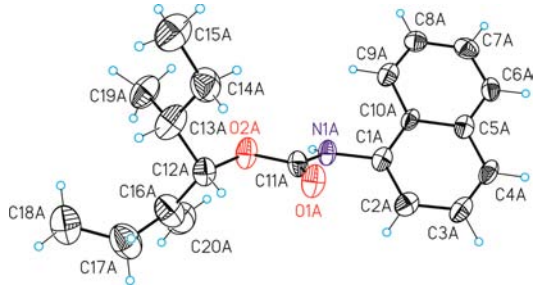


Figure 2. ORTEP Plot (thermal ellipsoids shown at 50% of probability level) of *syn*-**5**.

Encouraged by these results, the desymmetrization of substrates leading to enantioenriched dialkyl vinyl tertiary alcohols was pursued. This type of compounds cannot be prepared by asymmetric hydrogenation of carbonyl precursors, and the proposed desymmetrization strategy is an interesting variant to the classical C–C bond forming approach (enantioselective alkylation of a ketone with an organometallic derivative) toward enantioenriched dialkyl vinyl tertiary alcohols.[14] Substrate **1f** was therefore subjected to desymmetrization conditions (entry 6 in Table 3). The desired product **2f** was obtained with complete conversion, perfect chemoselectivity (**2f**:**3f** ratio >99:1), and very high enantioselectivity (92% ee; entry 6 in Table 3).

In short, a highly stereoselective catalytic hydrogenative desymmetrization based on Rh complexes derived from phosphine–phosphite ligands has been developed. The lead enantioselective catalyst, derived from the TADDOL-containing ligand **L13**, has given access to a set of highly enantioenriched secondary and tertiary alcohols (up to 92% ee). The presented results demonstrate the ability of the lead catalyst to differentiate between the two enantiotopic vinyl groups from the substrates. Moreover, the desymmetrization of a substrate containing two pro-stereogenic carbons (**1e**) proceeded with complete diastereoselectivity. Investigations to gain deeper insight in the reaction mechanism are currently underway.

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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.6b01088.

General procedure for catalytic experiments, preparation of substrates, spectral data of known and new compounds, crystallographic data, HPLC data from catalytic experiments (PDF)
X-ray data for *syn*-**5** (CIF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: avidal@iciq.es.

Notes

The authors declare no competing financial interest.

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(7) Ligand **L1** was selected for the initial studies due to its high catalytic performance in Rh-mediated asymmetric hydrogenations; see ref 6b,e.

(8) Determination of the enantiomeric excess of products **2** by chiral GC or HPLC analysis proved to be difficult. For this reason, products **2** were transformed into their benzoate esters **4** to facilitate the analysis (see the Supporting Information for details).

(9) The P−OP ligands presented in Figure 1 can be categorized in two principal groups: (i) geminal ligands **L2**−**L8** (phosphine and phosphite groups bound to the same carbon) incorporating a stereogenic axis and further stereogenic carbon or phosphorus centers (the Rh complexes derived from these ligands present strained asymmetric environments around the metal center; P−Rh−PO angle of ca. 80°; see ref 6g,i); (ii) vicinal ligands **L1** and **L9**−**L14** (phosphine and phosphite groups bound to vicinal carbons) containing two consecutive stereogenic C-atoms (these ligands also incorporate enantiopure BINOL- or TADDOL-derived phosphites).

(10) See the Supporting Information for further details.

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(13) The *anti*-diastereoisomer was not detected by ^{1}H NMR analysis of the reaction crude.

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