Pergamon

Tetrahedron: Asymmetry Vol. 6, No. 7, pp. 1675-1682, 1995
Copyright © 1995 Elsevier Science Ltd
Printed in Great Britain. All rights reserved
0957-4166/95 $9.50+0.00

0957-4166(95)00212-X

Enzyme catalysed resolution of 1,3-diarylpropan-1,3-diols

F. Levayer, C. Rabiller* and C. Tellier

Laboratoire de RMN et de Réactivité Chimique, URA CNRS 472, 2, rue de la Houssinière
F - 44072 NANTES Cédex 03 (FRANCE)

Abstract *: Candida Rugosa Lipase (AY 30, Amano) is shown to be a very efficient catalyst for the resolution of enantiomeric 1,3-diaryl-1,3-diols by means of the transesterification reaction using vinyl acetate as an acyl donor. This enzyme also exerts a great diasteroselectivity and a pronounced regioselectivity in the monoacylation reaction of these diols.*

Key words : 1,3-diols, lipases, enzymatic resolution, absolute configuration

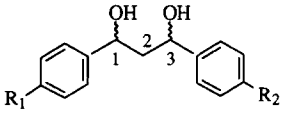
Chiral 1,3-diarylpropan-1,3-diols are compounds of particular interest because they can be converted subsequently into chiral 4,6-diaryl-1,3-dioxanes. The latter can be considered as mimic compounds for the transition state of an aldolisation reaction and we have used them as potential haptens to elicit antibodies with aldolase activity[1]. This work presents our results on the enzymatic resolution of these diols.

Asymmetric synthesis using enzymes and microorganisms in organic chemistry has been widely recognized as a useful tool for the synthesis of chiral synthons[2,3,4]. Lipases are easily available and these biocatalysts have been extensively used in the kinetic resolution of racemic esters. Furthermore, these enzymes which normally hydrolyse esters are also able to work in organic solvents and thus catalyse the esterification and the transesterification reactions. Using this methodology, regioselective and enantioselective reactions were successfully performed with 1,2-diols. A similar trend was also observed with 1,3-diols, particularly with 2-O-protected derivatives of glycerol[5] or with 1-substituted-1,3-diols[6,7]. However, biocatalysts have not been extensively used for the resolution of 1,3-disubstituted-1,3-diols[8,9]. To our knowledge 1,3-diarylpropan-1,3-diols have not been resolved using lipases preparations. A microorganism *(Trichoderma viride)* was shown to hydrolyse enantioselectively the diacetate of D,L-1,3-diphenylpropan-1,3-diol[10]. Other bio-methodologies have also been described recently. Starting from 1-phenylbutan-1,3-dione, Chênevert et al[11] obtained (S)-(+)-3-hydroxy-1-phenyl-1-butanone with both a high regio- and a high stereoselectivity in the presence of Baker's yeast hydrogenation system. Unfortunately the asymmetric hydrogenation of the remaining carbonyl group was not possible using this pathway. Furthermore we found this procedure totally unsuccessful with 1,3-diphenylpropan-1,3-dione. Another strategy which could be applied in our case is the one developed by

Takeshita[12]. This approach, using Baker's yeast asymmetric hydrogenation of 1-phenyl-2,3-epoxybutan-1-one followed by hydrogenation of the corresponding chiral alcohol, leads to a mixture of 1,3- and 1,2-diols. Chiral 1,3-diols may also be prepared by hydrogenation of 1,3-diones in the presence of Noyori BINAP's catalysts[13]. Some preliminary reactions performed on our 1,3-diarylpropan-1,3-diones with such catalysts were unsuccessful. The failure of this reaction was attributed to the bulkyness of the carbonyl functions. We therefore directed our efforts to the lipase catalysed transesterification of the 1,3-diols using vinyl acetate as an acyl donor. We avoided the microorganism pathway cited above because it could not be applied to a range of very insoluble 1,3-diaryl-1,3-diols and also because the procedure is less easy to handle than the enzymatic one.

Results and discussion

The two 1,3-diols **1** and **2** studied in this work are shown below:



1 $R_1 = R_2 = H$

2 $R_1 = p\text{-}CH_3O$, $R_2 = p\text{-}NO_2$

The choice of these model compounds was imposed for the following criteria :

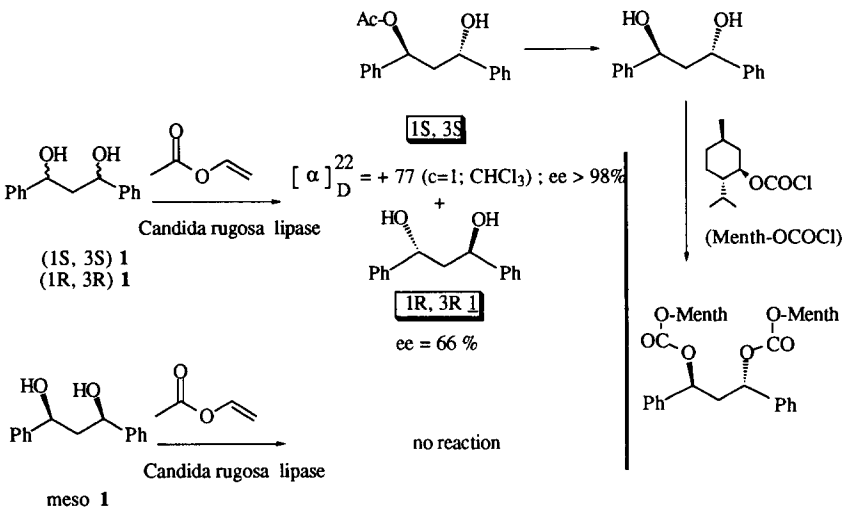
- the p-NO_2 substituent of **2** is necessary to ensure the further coupling of the corresponding 1,3-dioxane (hapten) with a carrier protein to build the antigen[13]. Furthermore the two p-substituents were found to be convenient to synthesize the ketol precursor of **2** (see below).

- the 1,3-diphenyl-1,3-diols **1** which are more stable and easier to handle than the analogues **2**, were used as model compounds in the enzymatic resolution.

The diols were prepared according to conventional methods. The 1,3-diphenylpropan-1,3-diol 1 was obtained as a diastereomeric mixture starting from styrene and benzaldehyde[14]. The hydrogenation, by $NaBH_4$, of the ketol synthesized from p-methoxyacetophenone and p-nitrobenzaldehyde led to diastereomeric diols 2. While the meso and the racemic diasteromers of **1** were easily separated by recrystallisation, we were unable to reproduce the same result with diols **2** because of their relative instability. The latter were thus transesterified using the diastereomeric mixture.

Considering the diols **1**, we screened some classical lipases *(Candida Rugosa, Porcine pancreatic, Pseudomonas fluorescens, Mucor meihi, Rhizopus)*. It is interesting to note that only *Candida Rugosa* lipase (AY 30 Amano) was able to catalyse efficiently the transesterification of the racemic 1,3-diol **1** leading to the corresponding monoacetate. Not a single trace of the diacetate was detected. Furthermore the meso diastereomer was shown to be a very poor substrate as no reaction at all occured over a ten day period of incubation. This lipase exerts not only a very high diastereoselectivity but also a very good enantioselectivity. Thus, after a conversion of 30%, the monoacetate and the remaining alcohol were separated. The former showed an optical activity with a specific rotation $[\alpha]_D^{22} = +77$ (c=1; $CHCl_3$). This ester was hydrolysed and the specific rotation of the diol obtained was $[\alpha]_D^{22} = +68$ (c=1; ethanol) or $[\alpha]_D^{22} = +49.5$ (c=1.2; $CHCl_3$) . The remaining 1,3-diol gave a specific rotation $[\alpha]_D^{22} = -38.8$ (c=1; ethanol) or $[\alpha]_D^{22} = -32.5$ (c=1.2; $CHCl_3$). Comparing these values to the ones reported in the literature [(1R,3R) and (1S,3S) **1** diols were shown to

present $[\alpha]_D^{22}$= -72.7 and +72.3 (c=10; ethanol) respectively[15], it becomes clear that the configuration preferred by the lipase is the (1S,3S)-1,3-diphenyl-1,3-diol **1**. The ee of this transesterification can be easily determined by means of the ^{13}C NMR spectra of the 1,3-di-(-)-menthylcarbonates of the diols (see scheme 1) which show particurlarly large splittings for the carbonyl signals (see figure I). Ee's values determined by this method were >98% for the product (no 1R,3R diol was detected either in the ^1H or in the ^{13}C spectra) and 66% for the remaining alcohol.



***Scheme 1** : Lipase catalysed transesterification of the 1,3-diphenylpropane-1,3-diols **1** .*

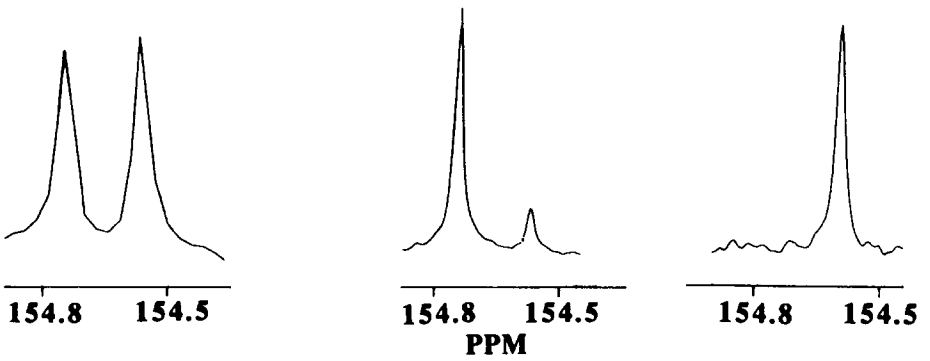
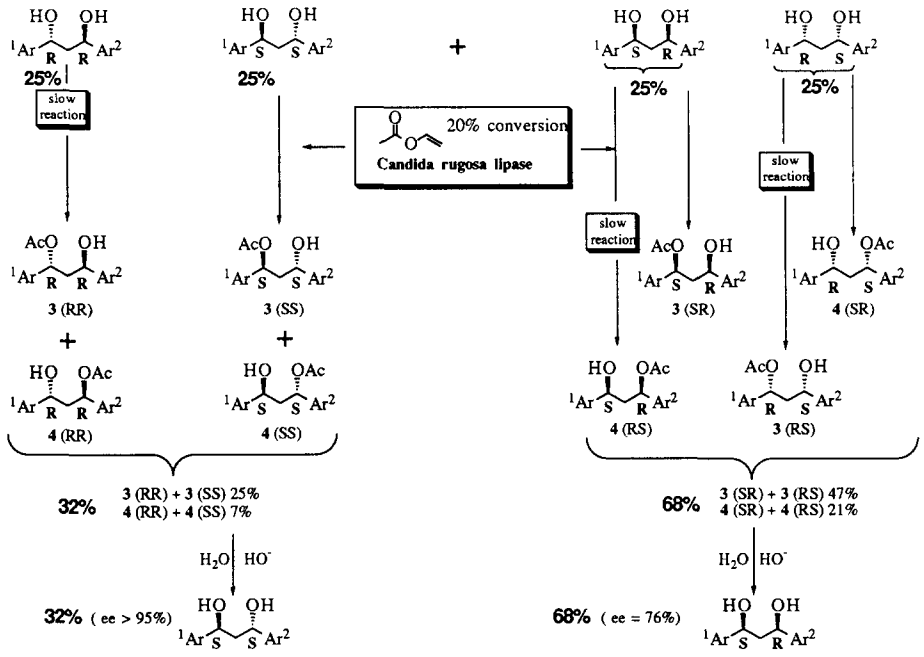


***Figure I** : ^{13}C NMR spectra (carbonyl groups only, solvent : pyridine-d_5) of the di-(-)-menthylcarbonates of the (1R,3R/1S,3S)-1,3-diphenyl-1,3-diol **1**. Left : from the racemic diol, middle : from the remaining alcohol (mainly 1R,3R), right : from the hydrolysis of the acetate produced in the enzymatic resolution, (nearly pure 1S,3S).*

The situation for the diols **2** is much more complicated because the transesterification was conducted on the equimolar mixture of the four stereoisomers and because of the regioselectivity problems. Again in this case,

only monoacetates were produced and eight stereoisomers are expected if no selectivity is observed. The scheme 2 describes the results obtained for this reaction.



***Scheme 2** : Lipase catalysed transesterification of the diastereomeric mixture of the 1,3-diols **2** (Ar[1] and Ar [2] represent the p-methoxyphenyl and the p-nitrophenyl groups respectively).*

Figure II shows the ^1H NMR spectrum of the CH proton (near the ester function) of the four monoacetates obtained after 20% conversion. The assignment of the positional isomers was made upon the assumption that the hydroxyl function near the p-methoxyphenyl (electron donor effect) should be more reactive than the hydroxyl group near the p-nitrophenyl substituent. The attribution of each diastereomeric monoacetate was made from the spectral analysis of the mixture of the diols obtained from the hydrolysis of these esters. The ^1H NMR spectrum of the latter have been identified by comparison with the known spectra of the diastereomeric 1,3-diphenylpropane-1,3-diols[16]. The integration (see spectrum figure II) allows a measurement of the diastereoselectivity and of the regioselectivity exerted by the lipase AY30. It is clear that the (1S,3R/1R,3S) diastereomer reacts faster than the (1R,3R/1S,3S) one (relative percentages : 68% and 32% respectively). This result, curiously opposite to that obtained with the diols 1 can be explained considering the bulkiness of the two p-substituants which strongly decreases the rate of the acylation. Each of these two diastereomers exists as two positional isomers. From the spectrum of figure II, it is also possible to determine the relative percentages of each. The following values were obtained : 47% (1S,3R/1R,3S)-1-acetoxy,1-p-methoxyphenyl,3-p-nitrophenylpropan-3-ol, 21% (1S,3R/1R,3S)-1-acetoxy,3-p-methoxyphenyl,1-p-nitrophenylpropan-3-ol, 25% (1R,3R/1S,3S)-1-acetoxy,1-p-methoxyphenyl,3-p-nitrophenylpropan-3-ol and 7% (1R,3R/1S,3S)-1-acetoxy,3-p-methoxyphenyl,1-p-nitrophenylpropan-3-ol.

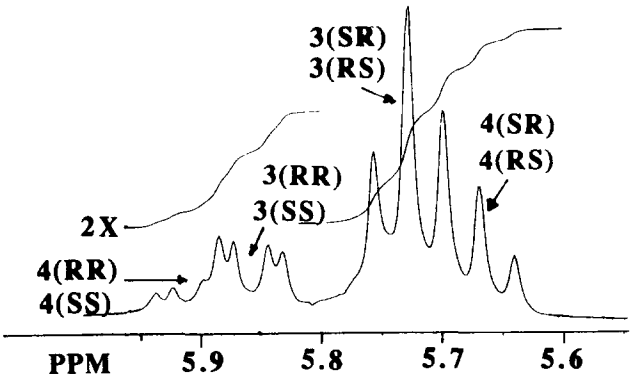


***Figure II** : ^1H NMR spectrum (proton near the acetoxy group only shown, solvent : $CDCl_3$) of the monoacetates obtained with the enzymatic transesterification of the diastereomeric mixture of the 3-p-methoxyphenyl,1-p-nitrophenylpropan-3-ol (2X on the spectrum means the integration of the signals between 5.8 and 6.0 ppm was multiplied by a factor two).*

The hydrolysis of the monoacetates gave a mixture of diastereomeric alcohols which were converted as above into di(-)-menthylcarbonates. The ^{13}C NMR spectrum of the di(-)-menthylcarbonates of a diastereomeric mixture of the 1,3-diols (60% 1S,3S/1R,3R and 40% 1R,3S/1S,3R) shows 8 carbonyl resonances which can be attributed to each diastereomer on the basis of their relative intensity. The same spectrum obtained from the derivatisation of the diols which have reacted shows only 6 carbonyl lines. Two of them (about 32%) belong to one of the (R,R) or (S,S)-dimenthylcarbonate as a nearly pure configuration, while the four remaining ones (68% of the total amount, 88/12% relative) represents the (S,R) and (R,S)-dimenthylcarbonates. Considering the enantioselectivity observed with the 1,3-diphenyl-1,3-diols, and the greater reactivity of the OH near the p-methoxy group, it was assuming that the configurations of the diols were (S,S) (32% of the total amount, ee > 95%) and (S,R) (68% of the total amount, ee ~ 76%, see scheme 2). The apparent poor resolution observed for the rac-(R,S)-diols is readily understandable as this value is a result of the regioselectivity and of the enantioselectivity exerted by the lipase. Considering the low conversion obtained in this reaction (only 20% after several days of incubation), no measurement of the ee of the remaining diols was undertaken.

Aknowledgments : Thanks are due to the French Ministère de la Recherche et de l'Enseignement (MRE) for a grant to F.L., to Amano for the generous gift of the lipases used and to K. Bartik for improvements to the English text.

Experimental

General :

The enzymatic preparation used were purchased from Amano (*Candida Rugosa* : lipase AY 30, *Pseudomonas fluorescens* : lipase PS, *Rhizopus* : lipase N conc. *Mucor* : lipase M-AP10) and from Sigma (porcine pancreatic lipase : Type II)

All the structures were determined by means of ^1H and ^{13}C NMR spectroscopy (WM 250 Bruker instrument). The spectra were recorded in $CDCl_3$ solutions for the diols and esters but in pyridin-d_5 for the carbonates. The attribution of the ^1H resonances for each diastereomer of **1** and of their (-)-dimenthylcarbonates is easily

achieved considering the type of spin systems for the methylene and methine protons. Thus the meso compound has an ABX_2 system while the racemic one gives a AA'XX' system[16]. Although the diols **2** (and their menthyl dicarbonates) are not "symmetrical" the AB parts look like those of ABX_2 and AA'XX' systems (particularly same coupling constants) thus allowing the identification.
The optical rotations were measured with a AA10 Optical Activity polarimeter.

Synthesis of the 1,3-diphenyl-1,3-propandiols ***1***.
The diacetates of the **1** diols were prepared according Zimmerman procedure[14]. However for the hydrolysis, it was necessary to modify the procedure described and particularly to use sodium hydroxide instead of the inefficient potassium hydroxide. Furthermore, we noticed that the rate of hydrolysis was quite different for each diastereomer. Thus after 3 hours of heating the diacetates in the presence of sodium hydroxide, the D,L-diol was formed only. A longer contact with the base leads to a mixture of the diastereomers and to the epimerisation of the DL form to the meso one. Thus, it is possible to obtain only the meso compound when a 24 h treatment is applied. The product is cristallised in toluene. The NMR parameters were consistent with the literature data[16].

Synthesis of the 1-p-nitrophenyl,3-p-methoxy-1,3-propandiols ***2***.

- Synthesis of the Ketol (1-p-methoxyphenyl, 3-p-nitrophenylpropan-2-one-3-ol)

To a solution of 15 g of p-methoxyacetophenone (0.1 mole) in 30 mL of ethanol and 100 mL of water, 15.1 g (0.1 mole) of p-nitrobenzaldehyde and 0.56 g (0.01 mole) of potassium hydroxide were added. The mixture is stirred for two-three hours at room temperature until the homogeneisation occurs. The ethanol is eliminated under reduced pressure without heating (the ketol decomposes very easily to the corresponding ethylenic ketone). The cristalline material thus obtained is filtered, washed with water, dried in the air and recristallised in ethanol (yield 90-95%).

- Hydrogenation of the ketol.

The ketol (0.1 mole) is partially dissolved in 150 mL of methanol. Then, small portions of sodium borohydride are added (0.2 mole) at room temperature under stirring. The mixture is stirred one hour more and 30 mL of water are added. Then the methanol is removed under reduced pressure and the solution is extracted with chloroform. The organic phase is dried over sodium sulfate and the solvent is removed under reduced pressure. The diols are purified over a silica gel column (eluent : pure CH_2Cl_2 to remove impurities and CH_2Cl_2/AcOEt : 1/1 to elute the diols, total yield 80-90%, mixture of the two diastereomers 50/50%). It should be noticed that these diols are not very stable in the presence of silica gel, so too long elution time should be avoided. Furthermore, the (RR/SS)-diol is degraded faster than the (RS/SR)-diastereomer leading to a further enrichment of the latter.

Compound **2** (R,R / S,S): RMN $^1H(CDCl_3)$, 1.94(ddd, 1H, -14.7, 8.0 and 4.0 Hz, H_2), 2.05(ddd, 1H, -14.7, 8.8 and 3.3 Hz, $H_{2'}$), 3.69(s, 3H, $OC\underline{H}_3$), 4.76(dd, 1H, 8.0 and 3.3 Hz, H_1), 4.91(dd, 1H, 8.8 and 4.0 Hz, H_3), 6.76(m, 2H, 8.8 Hz, p-nitrophenyl), 7.11(m, 2H, 8.8 Hz, p-methoxyphenyl), 7.34(m, 2H, 8.8 Hz p-methoxyphenyl), 8.08(m, 2H, 8.8 Hz, p-nitrophenyl); RMN $^{13}C(CDCl_3)$, 46.2(C_2), 55.3(OCH_3), 70.7(C_1), 71.1(C_3), 113.9(CH arom.), 123.5(CH arom.), 126.3(CH arom.), 126.7(CH arom.), 135.6(C arom.), 146.8(C arom.), 151.9(C arom.), 159.0(C arom.).

Compound **2** (R,S / S,R): RMN $^1H(CDCl_3)$, 1.76(dt, 1H, -14.65, 2.9 and 2.6 Hz, H_2), 1.97(dt, 1H, -14.65, 10.3 and 10.2 Hz, $H_{2'}$), 3.68(s, 3H, OCH_3), 4.84(dd, 1H, 10.3 and 2.9 Hz, H_1), 4.93(dd, 1H, 10.2 and 2.6 Hz, H_3), 6.74(m, 2H, 8.8 Hz, p-nitrophenyl), 7.14(m, 2H, 8.8 Hz, p-methoxyphenyl), 7.38 (m, 2H, 8.8 Hz p-methoxyphenyl), 8.02(m, 2H, 8.8 Hz, p-nitrophenyl); RMN ^{13}C ($CDCl_3$), 47.3(C_2), 55.3(OCH_3), 73.7(C_1), 74.6(C_3), 113.9(CH arom.), 123.6(CH arom.), 126.3(CH arom.), 126.9(CH arom.), 135.7(C arom.), 147.0(C arom.), 151.5(C arom.), 159.1(C arom.).

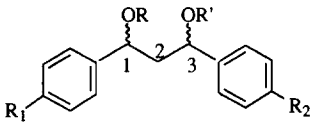
*Enzymatic resolution of 1,3-diols **1** and **2**.*

5 mmole of the diol were dissolved in a mixture of vinyl acetate (25 mL) and 25 mL of benzene (diol 1) or 25 mL of diethylether (diols **2**). Then 1g of the *Candida rugosa* lipase preparation (AY30 Amano) was added and the mixture was incubated for 10 days at room temperature. The reaction was followed by means of TLC (Merk 60 F_{254} silica gel plates, Rf = 0.62 (RS/SR), and Rf = 0,51 (RR/SS), $CHCl_3$/AcOEt : 3/1 for the monoacetates) . At the end of the 10 days, the conversion degree determined by means of proton NMR spectroscopy was 20 to 30%. The spectra showed the absence of the diacetates. The monoacetates were separated from the remaining diols with silica gel columns (same eluent as TLC in the case of diol **1**, pure $CHCl_3$ to elute the monoacetates of 2 and $CHCl_3$/AcOEt 1/1 for the diol **2**).

Monoacetate of diol **1** (S,S):

RMN ^1H ($CDCl_3$), 2.12(s,3H, CH_3CO), 2.12(ddd, 1H, -14.3, 10.3 and 3.7 Hz, CH_2), 2.32(ddd, 1H, -14.3, 9.9 and 3.3 Hz, CH_2), 4.75(dd, 1H, 9.9 and 3.7 Hz, CH-OH), 6.09(dd, 1H, 10.3 and 3.3 Hz, CH-OAc), 7.25-7.5(m, 10H, H arom.); RMN $^{13}C(CDCl_3)$, 21.1(CH_3), 46.5(CH_2), 70.7(CHOH), 73.4(CHOAc), 125.8(CH arom.), 126.5(CH arom.), 127.6(CH arom;), 128.0(CH arom.), 128.5(CH arom.), 140.6(C arom.), 143.9(C arom.), 170.7(C=O).

Monoacetates of the diols **2**.



R_1= p-CH_3O , R_2 = p-NO_2

- **R = CO-CH$_3$, R' = H** (R,R / S,S): RMN ^1H ($CDCl_3$), 2.04(s, 3H, CH_3CO), 1.9-2.4(m, 2H, CH_2), 3.70(s, 3H, OCH_3), 4.74(dd, 1H, 10.3 and 2.9 Hz, CH-OH), 5.95(dd, 1H, 10.2 and 3.3 Hz, CH-OAc), 6.7-8.1(m, 8H arom.); RMN ^{13}C ($CDCl_3$), 21.3(CH_3CO), 46.4(CH_2), 55.3(CH_3O), 69.5(C_3), 72.8(C_1), 114.1(CH arom.), 123.7(CH arom.), 126.5(CH arom.), 127.8(CH arom.), 131.7(C.arom.), 147.4(C.arom.), 151.5(C.arom.), 159.2(C.arom.), 171.5(CO).

- **R = H, R' = CO-CH$_3$** (R,R / S,S): RMN ^1H ($CDCl_3$), 2.05(s, 3H, CH_3CO), 1.9-2.4(m, 2H, CH_2), 3.72(s, 3H, OCH_3), 4.64(dd, 1H, 9.2 and 4.0 Hz, CH-OH), 6.02(dd, 1H, 10.2 and 4.0 Hz, CH-OAc), 6.7-8.1(m, 8H, arom.); RMN ^{13}C ($CDCl_3$), 21.1(CH_3CO), 46.0(CH_2), 55.3(CH_3O), 69.9(C_1), 72.3(C_3), 114.1(CH arom.), 123.8(CH arom.), 126.7(CH arom.), 127.5(CH arom.), 135.5(C.arom), 147.5(C.arom.), 151.2(C.arom.), 159.4(C.arom.), 170.6(CO).

- **R = CO-CH$_3$, R' = H** (R,S / S,R): RMN ^{1}H ($CDCl_3$), 1.91(s, 3H, C<u>H</u>$_3$CO), 1.9-2.4(m, 2H, C<u>H</u>$_2$), 3.72(s, 3H, OC<u>H</u>$_3$), 4.56(dd, 1H, 9.2 and 4.0 Hz, C<u>H</u>-OH), 5.82(t, 1H, 7.3 and 7.0 Hz, C<u>H</u>-OAc), 6.81(m, 2H arom. 8.8 Hz,), 7.23(m, 2H, 8.8 Hz), 7.36(m, 2H, 8.8 Hz), 8.06(m, 2H, 8.8 Hz); RMN ^{13}C ($CDCl_3$), 21.3(<u>C</u>H$_3$CO), 45.2(CH_2), 55.3(CH_3O), 70.7(C_3), 73.6(C_1), 114.1(CH arom.), 123.7(CH arom.), 126.5(CH arom.), 128.2(CH arom.), 131.4(C.arom.), 147.2(C.arom.), 151.5(C.arom.), 159.5(C.arom.), 170.4(CO).

- **R = H, R' = CO-CH3** (R,S / S,R): RMN ^{1}H ($CDCl_3$), 1.98(s, 3H, C<u>H</u>$_3$CO), 1.9-2.4(m, 2H, C<u>H</u>$_2$), 3.70(s, 3H, OC<u>H</u>$_3$), 4.43(dd, 1H, 8.0 and 5.3 Hz, C<u>H</u>-OH), 5.77(t, 1H, 7.0 Hz, C<u>H</u>-OAc), 6.79(m, 2H, 8.8 Hz), 7.11(m, 2H, 8.8 Hz), 7.42(m, 2H, 8.8 Hz), 8.10(m, 2H, 8.8 Hz); RMN ^{13}C ($CDCl_3$), 21.1(<u>C</u>H$_3$CO), 45.0(CH_2), 55.3(CH_3O), 70.8(C_1), 73.1(C_3), 114.1(CH arom.), 123.8(CH arom.), 127.0(CH arom.), 127.4(CH arom.), 135.4(C.arom.), 147.5(C.arom.), 151.2(C.arom.), 159.3(C.arom.), 170.0(CO).

Determination of the enantiomeric purities and of the absolute configuration.

In order to measure the enantioselectivity of the reaction and to determine the absolute configuration othe preferred enantiomer, the monoacetates were hydrolysed according to the procedure described above for the diacetates. The determination of the enantiomeric purity was achieved with the conversion of the diols in (-)-dimenthylcarbonates. Thus, 15 mg of the diol dissolved in 0.3 mL of pyridin-*d5* were introduced with 28 µL of (-)-menthylchloroformate in a 5 mm NMR tube. This mixture was allowed to react in an oven at 30°C for 12 hours. At this time the diol, according to the NMR spectrum, was completely consumed and no trace of the monomenthylcarbonate was apparent.

References

1. C. Rabiller, F. Levayer, C. Tellier, results to be published.
2. C.J. Sih , C.S. Chen , *Angew. Chem., Int. Ed. Eng.*, 1984, **23**, 570.
3. S. M. Roberts, *Nat. Prod. Rep.*, 1986, 489.
4. A. Heisler, C. Rabiller, R. Douillard, N. Goalou, G. Hagele, F. Levayer, *Tetrahedron : Asymm.*, 1993, **4**, 959.
5. V. Kersher, W. Kreiser, *Tetrahedron Lett.*, 1987, **28**, 531-536.
6. J. Weidner, F. Theil, H. Schick, *Tetrahedron : Asymm.*, 1994, **5**, 751-754.
7. A.J.M. Janssen, A.J.H. Klunder, B. Zwanenburg, *Tetrahedron*, 1991, **47**, 7409-7416.
8. A. Mattson, N. Öhmer, K. Hult, T. Norin, *Tetrahedron : Asymm.*, 1993, **4**, 925-930.
9. U. Goergens, M. Schneider, *J. Chem. Soc., Chem. Comm.*, 1991, 1066-1068.
   F. Theil, *Catalysis Today*, 1994, **22**, 517-536.
10. K. Yamamoto, H. Ando, H. Chikamatsu, *J. Chem. Soc., Chem. Commun.*, 1987, 354-355.
11. R. Chênevert, S. Thiboutot, *Can. J. Chem.*, 1986, **64**, 1599-1601.
12. M. Takeshita, M. Miura, Y. Unuma, *J. Chem. Soc., Perkin Trans.*, 1993, 2901-2905.
13. M. Kitamura, T. Okhuma, S. Inoue, N. Sayo, H. Kumobayashi, S. Akutagawa, T. Ohta, H. Takaya, R. Noyori, *J. Amer. Chem. Soc.* , 1988, **110**, 629-631.
14. H.E. Zimmerman, J. English, *J. Amer. Chem. Soc.*, 1954, **76**, 2285-2290.
15. K. Ito, T. Harada, A. Tai, *Bull. Chem. Soc. Jpn.*, 1980, **53**, 3367-3368.
16. J.P. Deprés, C. Morat, *J. Chem. Educ.*, 1992, **69**, A232-A239.

(*Received in UK* 5 *May* 1995; *accepted* 14 *June* 1995)