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A One-Step Procedure for the Monoacylation of Symmetrical 1,2-Diols

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A series of lanthanide (III) salts have been shown to catalyze the monoacylation of symmetrical 1,2-diols by carboxylic acid anhydrides with surprisingly high selectivity.

Introduction

The monoacylation of diols is an important challenge in organic synthesis.[1−3] While sterically or electronically different hydroxyls may be selectively modified with ease, methods for the monofunctionalization of similar hydroxyl groups are decidedly fewer in number. The problem is that both hydroxyl groups react at a similar, if not the same, rate and thus even with 1 equiv of reagent, a statistical mixture of starting diol and mono-/bisacylated products are formed (Figure 1). Several strategies have been attempted with the aim to overcome this problem. These less than satisfactory procedures include tedious and laborious continual extraction methods,[1] heterogeneous or solid supported methods,[2] and the opening of a variety of cyclic "acetal-like" systems.[3] All of these systems, however, suffer from serious drawbacks: complicated isolation protocol,[1] limited number of substrates, use of toxic reagents[3b] and/or noncatalytic systems,[3c] and procedures involving more than one chemical step.[3d,e] We have recently reported an alternative to these procedures using our newly discovered lanthanide(III)-catalyzed acylation reaction.[4] This system has the potential to overcome all of the above problems.

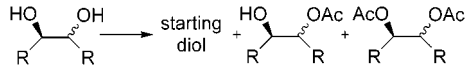

FIGURE 1.

Traditionally, the acylation of hydroxyl groups has been carried out using either an acyl halide or anhydride in the presence of a base and a nucleophilic activating agent. A fundamentally different approach is the use of a Lewis acid to activate the acylating agent toward nucleophilic attack by the hydroxyl group. Lewis acids have been used with varying degrees of success over the years to acylate alcohols.[5] The most useful of these systems involve the use of a carboxylic acid anhydride and a Lewis acid such as $TiCl(OTf)_3$, $TiCl_4$ and $AgClO_4$, $MgBr_2$, or $Sc(OTf)_3$.[6] These systems acylate the simple alcohols reported in good to high yields, but when molecules containing several hydroxyl functions are employed, multiple nonselective acylations occur.[7] Recently, there have been several reports of selective Lewis acid catalyzed acylations of diols.[2d] In these systems the Lewis acid is preabsorbed onto a solid support, such as silica gel or alumina. Selectivity in these systems, however, extends only to the differentiation of a primary alcohol over a sterically more encumbered one. In 1998, the groups of Holton[8] and Scheeren[9] independently reported the remarkable lanthanide(III) salt catalyzed C(10) selective acylation of 10-DAB. This procedure overturned the widely held belief that the C(7) hydroxyl

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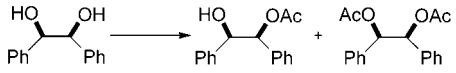
TABLE 1. $CeCl_3$-Catalyzed Reaction of Ac_2O with *meso*-Hydrobenzoin



1a **1b** **1c**

entry	concn (M)	amt of $CeCl_3$ (mol %)	amt of Ac_2O (equiv)	time (h)	ratio[a] (**a**/**b**/**c**)
1	0.366	0	10	44	84/14/02
2	0.366	10	10	23	05/90/05
3	0.366	10	1	20	21/77/02
4	no THF	10	10	48	42/42/16
5[b]	0.366	10	10	23	05/95/00
6[b]	0.732	10	10	23	50/50/00
7[b]	0.183	10	10	23	30/60/10

[a] Product ratios determined by 300 MHz ^{1}H NMR analysis. [b] Run at 0 °C for 7 h and then warmed to room temperature and stirred for a further 16 h.

group of 10-DAB was more reactive.[10] Intrigued by this reversal of selectivity, we decided to investigate the scope of lanthanide(III)-catalyzed acylation reactions to see if this alternate reactivity was a general phenomenon. We now wish to report the further results of our investigations[4] into the scope of our monoacylation reaction.

Results and Discussion

Use of Lanthanide(III) Chlorides as Monoacylation Catalysts. Studies focused on the idea that it might be possible to selectively acylate one hydroxyl group in a symmetrical diol. Initially, the acylation of *meso*-hydrobenzoin with acetic anhydride in the presence of 10 mol % of anhydrous $CeCl_3$ was chosen, as these were the optimal conditions from the work on 10-DAB.[8] In addition, we decided to impose upon ourselves an arbitrary set of parameters: that the reaction should (i) not require more that 10 equiv of acylating agent, (ii) not require more that 10 mol % of lanthanide(III) salt as a catalyst, and (iii) not take more than 24 h to give a synthetically useful yield of product.

When *meso*-hydrobenzoin was treated with 10 equiv of acetic anhydride in THF, it was found that the rate of acylation was very slow, with the reaction containing 84% *meso*-hydrobenzoin even after nearly 2 days (entry 1, Table 1). When the same reaction was rerun in the presence of 10 mol % $CeCl_3$, a remarkable acceleration was noted. After 23 h, there was only 5% *meso*-hydrobenzoin present in the reaction mixture. What was even more surprising was that 90% of the mixture was the monoacylated product **1b**, with only 5% of the bisacylated product **1c** formed (entry 2, Table 1). The reaction was discovered to be synthetically useful when only 1 equiv of acetic anhydride was employed, there being 77% conversion to the monoacylated product within 20 h (Entry 3, Table 1). Selectivity for the monoacylated product was also increased by running the reaction at a lower temperature (entry 5, Table 1), but the enhancement was viewed as not so great as to warrant adopting the lower temperature for subsequent studies.

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TABLE 2. Survey of Other Lanthanide(III) Chlorides as Acylation Catalysts[a]

cat.[b]	**1a**/**1b**/**1c** (time, h)	**2a**/**2b**/**2c** (time, h)	**3a**/**3b**/**3c** (time, h)
$CeCl_3$	05/90/05 (23)	56/44/00 (24)	100/00/00 (24)
$DyCl_3$	00/89/11 (16)	26/70/04 (24)	00/87/13 (48)
$YbCl_3$	00/95/05 (4)	16/84/00 (24)	

[a] Ratios determined by 300 MHz ^{1}H NMR analysis. [b] In all cases, the amount of catalyst used was 10 mol %.

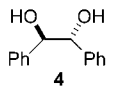
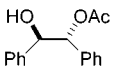
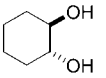
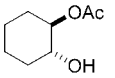
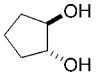
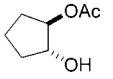
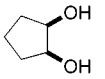
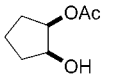
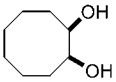
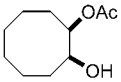
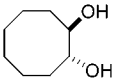
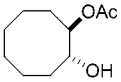
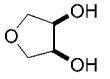
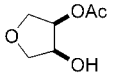
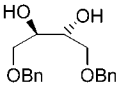
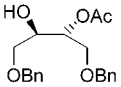
Having shown that it was possible to monoacylate *meso*-hydrobenzoin with a very high selectivity, it was desirable to see if this procedure was applicable to other symmetrical 1,2-diols. The diols which were chosen were *cis*-1,2-cyclohexanediol **2** and *meso*-2,3-butanediol **3**, as these have been the subject of earlier monoacylation and desymmetrization studies.[3] When **2** was subjected to the reaction conditions, we were disappointed to find that the reaction was very slow, producing only 44% of the monoacylated product **2b** after 24 h. The monoacylation of **3** did not proceed at all within any acceptable time frame.

At this time we became aware of a report which showed that the ability of lanthanide(III) salts (absorbed onto silica gel) to catalyze acylation reactions increased with increasing atomic mass.[2e] This was explained by the increased Lewis acidity of the salts due to the well-known lanthanide contraction effect. When the acylation reactions of **2** and **3** were rerun using $DyCl_3$ and $YbCl_3$, it was found that respectable yields of the monoacylated products **2b** and **3b** were formed (Table 2). It was also discovered that the use of these salts decreased the reaction time for the monoacylation of *meso*-hydrobenzoin from 23 h (10 mol % $CeCl_3$) to only 4 h (10 mol % $YbCl_3$) with no loss in selectivity.

Encouraged by the results obtained using $YbCl_3$ as an acylation catalyst, we acylated a selection of other *meso* and C2-symmetric 1,2-diols using the $YbCl_3$/acetic anhydride procedure. It was found that very high levels of mono selectivity were achieved for all the 1,2-diols investigated (Table 3). One notable feature of the reaction which might have implications for the mechanism of the acylation is that, in general, C2-symmetric diols were acylated at a faster rate than the corresponding *meso*-diols. It is possible that this hints at a preferred conformation for coordination or chelation of the diol to the lanthanide(III) salt during the acylation reaction (Figure 2).

Our working hypothesis is that both the diol and the anhydride coordinate to the lanthanide(III) salt. This complex then enables the "intramolecular" transfer of an acyl group from the anhydride to the diol. The resultant seven-membered chelate is less stable and is replaced by a five-membered diol chelate. If the chelated diol is acylated at a much greater rate than any nonchelated substrate, this would account for both the rate enhancement and the mono selectivity seen. The observation that C2 diols are acylated at a faster rate than *meso*-diols can also be explained using this rationale. In the case of a *meso*-diol, chelation to the metal salt might result in an unfavorable eclipsing interaction between the R groups, which is not present in the case of the C2 diol (Figure 2). This interaction would slow the rate of chelation and, hence, the rate of acylation. Work is currently underway

TABLE 3. Monoacylation of Representative Symmetrical 1,2-Diols using $YbCl_3$

Diol (**a**)	Mono-acylated (**b**)	Yield (%)
 **4**		100
 **5**		93
 **6**		64[a]
 **7**		92
 **8**		78
 **9**		86
 **10**		95
 **11**		90

[a] 26% of the bis-acylated product was also formed.

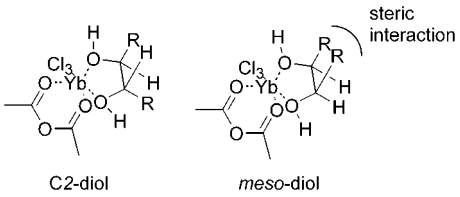


FIGURE 2.

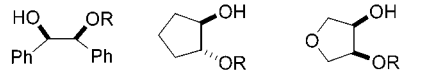


FIGURE 3.

to elucidate the exact role of the lanthanide(III) chloride in the acylation reaction and will be reported in due course.[11a,b]

Acetic anhydride is not the only carboxylic acid anhydride which may be used in this reaction (Figure 3). *meso*-Hydrobenzoin **1a** can be treated with benzoic anhydride, propionic anhydride, or *tert*-butyl pyrocarbonate to give both the monobenzoate **1d** or the monopropionate **1e** in 91% and the mono-*tert*-butyloxycarbonate **1f** in 100% yield. *trans*-1,2-Cyclopentanediol **6a** was converted to the monobenzoate **6d** in 80% yield, and 1,4-anhydroerythritol **10a** was converted to the monobenzoate **10d** in 100% yield.

TABLE 4. Effect of Solvent on the Monobenzoylation of *meso*-Hydrobenzoin[a]

entry	solvent	**1a** (%)	**1d** (%)	bis product (%)
1	THF	9	91	0
2	petrol	100	0	0
3	CH_2Cl_2	0	100	0
4	EtOAc	24	76	0
5	DMF	100	0	0
6	MeCN	39	61	0
7	ether	37	63	0
8	water	100	0	0

[a] Ratios determined by 400 MHz ^{1}H NMR analysis after 23 h. $YbCl_3$ (10 mol %) used as catalyst.

The next parameter to be investigated was the effect of solvent on the reaction. This was in an attempt to reduce the reaction time for the monobenzoylation procedure which, even when $YbCl_3$ was used, took 23 h. To this end a range of solvents were surveyed (Table 4). All of the solvents used were inferior to THF, with the exception of CH_2Cl_2, which was slightly superior in terms of reaction rate. In the case of petrol and water it can be assumed that the lack of either substrate or catalyst solubility resulted in no reaction. A possible reason for the higher conversion in CH_2Cl_2 is that this is a non-coordinating solvent and, as such, the Lewis acid would be more available for coordination to the reactants and would be "activated" by the lack of stabilization from solvent ligands. With CH_2Cl_2 as a solvent it also proved possible to reduce the loading of $YbCl_3$ to 1 mol % for the monoacylation of *meso*-hydrobenzoin with acetic anhydride, although the reaction now took 19 h.

Use of Ytterbium(III) Triflate as a Monoacylation Catalyst. Recently, the use of $Yb(OTf)_3$ as a Lewis acid has received much attention in the literature,[12] including as an acylation catalyst.[6,9] It was reasoned that the greater electron-withdrawing nature of the triflate groups would make $Yb(OTf)_3$ a stronger Lewis acid than $YbCl_3$. As such, $Yb(OTf)_3$ might be expected to increase the rate of the monoacylation reaction even further. To test this hypothesis, a solution of *meso*-hydrobenzoin in THF was treated with acetic anhydride in the presence of 10 mol

(11) (a) While pondering the mechanism of this acylation, we considered the possibility that an acyl chloride, generated in situ, might be the active acyl donor. However, experiments utilizing acyl chlorides showed that there was a significant nonselective background reaction. Although lanthanide(III) salts did accelerate these reactions, they were still found to be nonselective. At this time we do not believe that acyl chlorides are involved in these reactions. (b) A reviewer has suggested an alternative model in which one hydroxyl group of the diol and one carbonyl group of the anhydride are complexed with the lanthanide-(III) salt, so that the uncoordinated hydroxyl remains sufficiently nucleophilic to attack the activated carbonyl of the anhydride. We are currently engaged in mechanistic studies to understand the precise role of the lanthanide(III) salt, although at this time it remains unclear.

(12) For a selection of very recent examples see: Annunziata, R.; Benaglia, M.; Raimondi, L. *Tetrahedron* **2001**, *57*, 10357. Suga, H.; Kakehi, A.; Ito, S.; Inoue, K.; Ishida, H.; Ibata, T. *Bull. Chem. Soc. Jpn.* **2001**, *74*, 1115. Curini, M.; Epifano, F.; Marcotullio, M. C.; Rosati, O. *Tetrahedron Lett.* **2001**, *42*, 4593. Takhi, M.; Rahman, A. A. H. A.; Schmidt, R. R. *Tetrahedron Lett.* **2001**, *42*, 4053. Likhar, P. R.; Kumar, M. P.; Bandyopadhyay, A. K. *Synlett* **2001**, 836. Bickley, J. F.; Hauer, B.; Pena, P. C. A.; Roberts, S. M.; Skidmore, J. *J. Chem. Soc., Perkin Trans. 1* **2001**, 1253 and references therein.

% of $Yb(OTf)_3$. The acylation was both rapid and nonselective, generating the bisacylated product **1c** exclusively in under 1 h. The ^1H NMR of the crude reaction mixture showed that the $Yb(OTf)_3$ also promoted side reactions (polymerization/ring opening) of the THF solvent. When the amount of $Yb(OTf)_3$ was reduced to 1 mol %, THF side reactions and selectivity still proved a problem, with only 17% of **1b** being formed in 4 h. The mass balance was bisacylated product **1c**. While $Yb(OTf)_3$ was far too active to be of use in the monoacylation of diols with acetic anhydride, it was possible that its increased activity was ideal for monobenzoylation in CH_2Cl_2.

Indeed, it was found that *meso*-hydrobenzoin could be monobenzoylated in the presence of 10 mol % of $Yb(OTf)_3$ in CH_2Cl_2 with only 3 equiv of benzoic anhydride in 70% yield after 23 h, the remainder being unreacted *meso*-hydrobenzoin. While under these conditions the reaction time was unaffected, the use of only 3 equiv of benzoic anhydride greatly simplified the workup and isolation procedure. Conditions were also developed utilizing only 0.1 mol % of $Yb(OTf)_3$ and 10 equiv of acetic anhydride in CH_2Cl_2 to monoacylate *meso*-hydrobenzoin in 77% yield; the remainder of the material was unreacted diol.

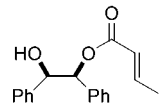
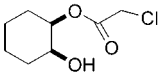
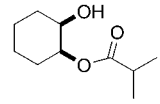
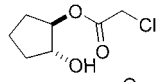
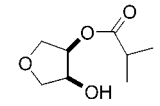
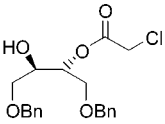
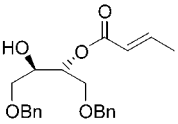
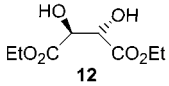
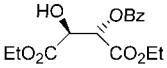
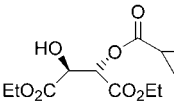
Use of Other Diol/Anhydride Systems. With these optimal conditions in hand, a number of diols were monoacylated with a variety of carboxylic acid anhydrides. As can be seen from Table 5, a range of cyclic, acyclic, functionalized, and heteroatom-containing diols can be used with no loss in selectivity. The reaction is also general for all anhydrides investigated: aromatic, cyclic alkyl, alkyl, branched alkyl, unsaturated, and halogen containing. In all cases the major product was the monoacylated compound, which could be isolated easily in good to excellent yields by either flash column chromatography or recrystallization.

Note on the Reaction Procedure and Conditions. During the initial stages of this work we were careful to use dry, distilled solvents and reagents. We also used anhydrous lanthanide(III) salts under an inert atmosphere of nitrogen gas. However, it became apparent that the reaction was very tolerant of variation in conditions: nondried or distilled THF or CH_2Cl_2, straight from the supplier, could be used in the reaction with no loss of reactivity or selectivity. Likewise, the reaction could be run open to the laboratory atmosphere and with hydrated lanthanide(III) salts, again with no loss in selectivity. Two factors did effect the rate of the reaction. One was the nature of the anhydride, with sterically more demanding anhydrides requiring longer reaction times. The second was the structure of the diol, with diols containing an additional oxygen functionality (tartrates, anhydroerythritol) acylating more rapidly than those which did not. In all systems studied, however, a synthetically useful yield of product was obtained within 24 h.

Conclusions

We have developed a selective and high-yielding one-step procedure for the monoacylation of symmetrical 1,2-diols, which is both reliable and experimentally straightforward. A wide range of diols and carboxylic anhydrides may be employed. The high tolerance and the straightforward nature of the reaction procedure make this a very useful addition to the organic chemist's tool box. Investigations are currently underway to understand the mechanism of the reaction and thus enable us to extend this procedure to other 1,*n*-diols and the enantiotopic desymmetrization of *meso* systems. Full details of these studies will be reported in due course.

TABLE 5

Diol (**a**)		Mono-acylated	Yield (%)
1	1g		97[a]
2	2d		65[a]
2	2e		81[a]
6	6e		88[a]
10	10e		80[a]
11	11d		90[a]
11	11e		33[a, b]
 12	12a		77[c]
12	12b		80[a]

[a] $YbCl_3$ (10 mol %) in THF. [b] Isolation difficulties; 400 MHz ^1H NMR analysis of the crude reaction mixture showed only the monoacylated product was present. [c] $YbCl_3$ (10 mol %) in CH_2Cl_2.

Experimental Section

General Considerations. All melting points are uncorrected. Optical rotations were measured in a 10 cm cell at ambient temperature in the stated solvent. Reaction progress was monitored using glass-backed TLC plates precoated with silica UV_{254} and visualized by using either UV radiation (254 nm) or ceric ammonium molybdate. Column chromatography was performed using silica gel 60 (220−240 mesh), with the solvent systems indicated in the relevant experimental procedures. Diethyl ether (referred to throughout as ether) and THF were distilled from sodium−benzophenone ketyl, and methylene chloride was distilled from calcium hydride. All other reagents were used as received from commercial suppliers unless stated otherwise in the appropriate text.

General Procedure for the $YbCl_3$-Catalyzed Monoacylation of Diols with Carboxylic Acid Anhydrides. Carboxylic acid anhydride (4.3 mmol) was added to a stirred solution of diol (0.43 mmol) and $YbCl_3$ (0.043 mmol, 10 mol % with respect to diol) in either THF or CH_2Cl_2 (1.2 mL) under a nitrogen atmosphere. When the reaction was complete by

TLC (EtOAc−hexane mixtures) it was diluted with EtOAc and washed successively with saturated sodium bicarbonate solution (×3), water, and brine. The organic layer was separated and dried ($MgSO_4$) and the solvent evaporated to yield crude monoacylated material. The crude material was purified via flash column chromatography (EtOAc−hexane mixtures) to provide the monoacylated products in good yields.

Monobenzoylation of *meso*-Hydrobenzoin using Yb(OTf)$_3$ Catalyst. A suspension of *meso*-hydrobenzoin (184 mg, 0.86 mmol), benzoic anhydride (570 mg, 2.58 mmol), and Yb(OTf)$_3$ (53 mg, 0.086 mmol) in CH_2Cl_2 (2.4 mL) was stirred under a nitrogen atmosphere for 23.5 h. After this time the reaction mixture was diluted with Et_2O and washed successively with saturated sodium bicarbonate solution (×3), water, and brine. The organic layer was separated and dried ($MgSO_4$) and the solvent evaporated to yield crude monoacylated material. The crude material was purified via flash column chromatography (1:1 EtOAc−hexane) to provide the monobenzoate product (192 mg, 70%).

Monoacylation of *meso*-Hydrobenzoin using Yb(OTf)$_3$ Catalyst. Acetic anhydride (16.0 mL, 172.0 mmol) was added to a stirred solution of *meso*-hydrobenzoin (3.68 g, 17.2 mmol) and Yb(OTf)$_3$ (11 mg, 0.017 mmol, 0.1 mol % with respect to diol) in CH_2Cl_2 (48 mL) under an atmosphere of nitrogen. After 22.5 h the reaction mixture was poured into a saturated solution of sodium bicarbonate and stirred rapidly for 30 min. After this time the organics were separated and dried ($MgSO_4$) and the solvent evaporated to yield the crude product. The product was purified by recrystalization from EtOAc−hexane to yield the monoacetate (3.39 g, 77%).

Cyclopropanecarboxylic Anhydride. A solution of cyclopropanecarboxylic acid (5.00 g, 0.06 mol) and DCC (6.13 g, 0.03 mol) in CH_2Cl_2 (63.0 mL) was stirred for 24 h. The resulting precipitate was filtered off via a plug of Celite and the filtrate evaporated to yield cyclopropanecarboxylic anhydride (3.76 g, 75%), which was used without further purification.

IR ($CHCl_3$): 2932, 2858, 1810, 1732, 1369, 1080, 1054, 991 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 1.70 (1H, m), 1.19−1.15 (2H, m), 1.06−1.01 (2H, m).

***meso*-Hydrobenzoin Monoacetate (1b).** Data were identical with those reported in the literature.[13]

***meso*-Hydrobenzoin Monobenzoate (1d).** Data were identical with those reported in the literature.[14]

***meso*-Hydrobenzoin Monopropionate (1e).** Mp: 86−87 °C. IR ($CHCl_3$): 3692, 3605, 1733, 1601, 1082, 766 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.34−7.27 (10H, m), 5.94 (1H, d, J = 6.1 Hz), 4.99 (1H, d, J = 6.1 Hz), 2.40 (1H, bs), 2.30 (2H, q, J = 7.6 Hz), 1.05 (3H, t, J = 7.6 Hz). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 173.2 (s), 139.7 (s), 136.3 (s), 128.4 (d), 128.3 (d), 128.1 (d), 128.0 (d), 127.7 (d), 127.0 (d), 78.6 (d), 76.4 (d), 27.7 (t), 8.9 (q). MS (EI): m/z 270 $(M)^+$, 253 $(M - OH)^+$. Anal. Calcd for $C_{17}H_{18}O_3$: C, 75.58; H, 6.67. Found: C, 75.18; H, 6.61.

***meso*-Hydrobenzoin Mono-*tert*-butyloxycarbonyl (1f).** Mp: 125−127 °C. IR ($CHCl_3$): 3597, 2983, 1741, 1455 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.34−7.27 (10H, m), 5.72 (1H, d, J = 5.8 Hz), 5.05 (1H, dd, J = 5.8, 3.3 Hz), 2.26 (1H, d, J = 3.6 Hz), 1.39 (9H, s). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 152.6, 139.4, 136.1, 128.5, 128.2, 128.2, 128.0, 127.8, 127.0, 82.6, 81.7, 76.2, 27.7. MS (CI NH_3): m/z 332 $(M + NH_4)^+$, 258 $(M + H - {}^t\mathrm{Bu})^+$, 214 $(M + H - {}^t\mathrm{Bu} - CO_2)^+$; found $M + NH_4^+$ 332.1864, $C_{19}H_{26}NO_4$ requires $M + NH_4$ 332.1862.

***meso*-Hydrobenzoin Mono-*trans*-crotonate (1g).** Mp: 97−100 °C. IR ($CHCl_3$): 3594, 2962, 1718, 1657, 1453, 1316, 1102, 968, 908 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.52−7.00 (10H, m), 6.95 (1H, m), 5.97 (1H, d, J = 5.6 Hz), 5.85 (1H, dq, J = 15.7, 1.3 Hz), 5.04 (1H, m), 2.24 (1H, d, J = 3.8 Hz), 1.86 (3H, dd, J = 6.9, 1.3 Hz). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 165.4 (s), 145.6 (d), 139.6 (d), 136.5 (d), 128.4 (d), 128.2 (d), 128.1 (d), 128.0 (d), 127.7 (d), 127.0 (d), 122.4 (d), 78.8 (d), 76.5 (d), 18.1 (q). MS (CI NH_3): m/z 300 $(M + NH_4)^+$, 283 $(M + H)^+$, 265 $(M - OH)^+$.

***cis*-Cyclohexanediol Monoacetate (2b).** Data were identical with those reported in the literature.[15]

***cis*-Cyclohexanediol Monochloroacetate (2d).** Mp: 59−61 °C. IR ($CHCl_3$): 3438, 1748, 1646, 985 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 5.01 (1H, dt, J = 7.5, 2.7 Hz), 4.13 (1H, d, J = 14.9 Hz), 4.09 (1H, d, J = 14.9 Hz), 3.88 (1H, dt, J = 7.7, 2.7 Hz), 2.75 (1H, bs), 1.89 (1H, m), 1.78−1.53 (5H, m), 1.43−1.31 (2H, m). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 167.0 (s), 75.9 (d), 69.0 (d), 41.0 (t), 30.1 (t), 29.9 (t), 21.6 (t), 21.1 (t). MS (CI NH_3): m/z 210 $(M + NH_4)^+$, 193 $(M + H)^+$, 176, 159, 134, 116. Anal. Calcd for $C_8H_{13}O_3Cl$: C, 49.88; H, 6.80. Found: C, 49.80; H, 6.87.

***cis*-Cyclohexanediol Monoisobutanoate (2e).** Clear oil. IR ($CHCl_3$): 3541, 2937, 1732, 1694, 1520 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 4.95 (1H, dt, J = 7.6, 2.8 Hz), 3.88 (1H, m), 2.60 (1H, sept, J = 7.0 Hz), 1.91−1.54 (6H, m), 1.44−1.35 (2H, m), 1.21 (3H, d, J = 7.0 Hz), 1.20 (3H, d, J = 7.0 Hz). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 177.0 (s), 73.7 (d), 69.6 (d), 34.3 (s), 30.3 (d), 27.2 (t), 21.8 (t), 21.4 (t), 19.2 (q), 19.1 (q). MS (CI NH_3): m/z 204 $(M + NH_4)^+$, 187 $(M + H)^+$; found M + H 187.1336., $C_{10}H_{19}O_3$ requires M + H 187.1334.

***meso*-2,3-Butanediol Monoacetate (3b).** Data were identical with those reported in the literature.[13b,16]

Hydrobenzoin Monoacetate (4b). Data were identical with those reported in the literature.[17]

***trans*-Cyclohexanediol Monoacetate (5b).** Data were identical with those reported in the literature.[15b,18]

***trans*-Cyclopentanediol Monoacetate (6b).** Data were identical with those reported in the literature.[18]

***trans*-Cyclopentanediol Monobenzoate (6d).** Data were identical with those reported in the literature.[19]

***trans*-Cyclopentanediol Monochloroacetate (6e).** Mp: 37−39 °C. IR ($CHCl_3$): 3605, 2955, 2879, 1731, 1412, 1315, 1200, 1147, 1036 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 4.91 (1H, dt, J = 7.5, 3.8), 4.14 (1H, m), 4.07 (2H, s), 2.16 (1H, m), 2.04 (1H, m), 1.74 (4H, m). ^{13}C NMR ($CDCl_3$, 100 MHz): 168.5, 85.6, 78.0, 41.4, 32.8, 30.2, 21.8. MS (CI NH_3): m/z 196.0 $(M + NH_4)^+$, 162.0 $(M + NH_4 - Cl)^+$, 145.0 $(M + NH_4 - Cl - OH)^+$, 120 $(M + NH_4 - C(O)CH_2Cl)^+$, 102 $(M + NH_4 - C(O)CH_2Cl - H_2O)^+$; found $M + NH_4^+$ 196.0742, $C_7H_{15}NO_3Cl$ requires M 196.0740.

***cis*-Cyclopentanediol Monoacetate (7b).** Data were identical with those reported in the literature.[15]

***cis*-Cyclooctanediol Monoacetate (8b).** Clear oil. IR (CH_2Cl_2): 3597, 2859, 1732, 1478, 1367, 1046, 965 cm^{-1}. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 5.03 (1H, dt, J = 9.3, 2.5 Hz), 3.95 (1H, m), 2.07 (3H, s), 1.82−1.50 (12H, m). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 170.7 (s), 76.9 (d), 71.7 (d), 30.2 (t), 27.7 (t), 27.0 (t), 25.4 (t), 24.6 (t), 21.8 (t), 21.4 (q).

***trans*-Cyclooctanediol Monoacetate (9b).** Data were identical with those reported in the literature.[20]

Anhydroerythritol Monoacetate (10b). Data were identical with those reported in the literature.[21]

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(14) Glass. B. D.; Goosen, A.; McCleland, C. W. *J. Chem. Soc., Perkin Trans. 2* **1993**, 2175.

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(16) Bisht, K. S.; Parmar, V. S.; Crout, D. H. G. *Tetrahedron: Asymmetry* **1993**, *4*, 957.

(17) Brugidou, J.; Christol, H.; Sales, R. *Bull. Chem. Soc. Fr.* **1974**, 2027. Wallace, T. W.; Wardell, I.; Li, K.-D.; Leeming, P.; Redhouse, A. D.; Challand, S. R. *J. Chem. Soc., Perkin Trans. 1* **1995**, 2293. Oikawa, M.; Wada, A.; Okazaki, F.; Kusumoto, S. *J. Org. Chem.* **1996**, *61*, 4469.

(18) Fang, C.; Ogawa, T.; Suemune, H.; Sakai, K. *Tetrahedron: Asymmetry* **1991**, *2*, 389.

(19) Anchisi, C.; Maccioni, A.; Maccioni, A. M.; Podda, G. *Gazz. Chim. Ital.* **1983**, *113*, 73.

(20) Posner, G. H.; Rogers, D. Z. *J. Am. Chem. Soc.* **1977**, *99*, 8208.

Anhydroerythritol Monobenzoate (10d). Mp: 68−72 °C. IR ($CHCl_3$): 3592, 2878, 1721, 1602, 1452, 1277, 1117, 1070 cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 8.06 (2H, dd, J = 8.0, 1.4 Hz), 7.57 (1H, tt, J = 7.4, 1.2 Hz), 7.43 (2H, t, J = 7.4 Hz), 5.36 (1H, app dd, J = 9.7, 5.5 Hz), 4.55 (1H, app q, J = 5.5 Hz), 4.14 (1H, dd, J = 10.1, 5.8 Hz), 4.02 (1H, dd, J = 9.3, 5.7 Hz), 3.98 (1H, dd, J = 10.1, 4.0 Hz), 3.78 (1H, dd, J = 9.3, 5.4 Hz), 2.85 (1H, bs). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 166.3, 133.4, 129.7, 129.4, 128.4, 74.2, 72.3, 70.9, 70.5. MS (CI NH_3): m/z 226 $(M + NH_4)^+$, 209 $(M + H)^+$, 109 $(M - H_2O)^+$, 105 $(PhCO)^+$; found M + H^+ 109.0816, $C_{11}H_{13}O_4$ requires M + H 209.0814.

Anhydroerythritol Monoisobutanoate (10e). Clear oil. IR ($CHCl_3$): 3589, 2936, 2877, 1732, 1602, 1461, 1388, 1076, 995 cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 5.14 (1H, td, J = 5.5, 4.0 Hz), 4.47 (1H, dt, J = 5.5, 5.5 Hz), 4.09 (1H, dd, J = 10.3, 5.8 Hz), 3.99 (1H, dd, J = 9.3, 5.8 Hz), 3.83 (1H, dd, J = 10.3, 3.9 Hz), 3.72 (1H, dd, J = 9.3, 5,5 Hz), 2.66 (1H, sept, J = 7.0 Hz), 1.22 (3H, d, J = 7.0 Hz), 1.21 (3H, d, J = 7.0 Hz). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 176.8, 73.5, 72.4, 71.2, 70.8, 34.0, 19.1, 19.0.

(2*R*,3*R*)-1,4-Bis(benzyloxy)-2,3-butanediol Monoacetate (11b). Oil. $[\alpha]_D$ = −2.84° (c = 0.1, $CHCl_3$). IR ($CHCl_3$): 3579, 2869, 1736, 1601, 1454, 1373, 1102, 1057 cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 7.38−7.27 (10H, m), 5.17 (1H, dt, J = 3.8, 3.8 Hz), 4.57 (1H, d, J = 12.0 Hz), 4.51 (2H, s), 4.48 (1H, d, J = 12.0 Hz), 4.08 (1H, m), 3.72 (1H, dd, J = 10.5, 4.6 Hz), 3.66 (1H, dd, J = 10.5, 5.1 Hz), 3.54 (1H, dd, J = 9.6, 4.6 Hz), 3.49 (1H, dd, J = 9.6, 6.0 Hz), 2.71 (1H, d, J = 4.7 Hz), 2.07 (3H, s). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 170.7, 137.7, 128.5, 127.9, 127.8, 73.6, 73.5, 72.2, 70.9, 70.0, 69.3, 27.9, 21.1. MS (CI NH_3): m/z 362 $(M + NH_4)^+$, 345 $(M + H)^+$, 327 $(M - OH)^+$, 237 $(M - OCH_2Ph)^+$, 147 $(M + H - O(CH_2Ph)_2)^+$.

(2*R*,3*R*)-1,4-Bis(benzyloxy)-2,3-butanediol Monochloroacetate (11d). Mp: 58−60 °C. $[\alpha]_D$ −3.3° (c = 0.3, $CHCl_3$). IR ($CHCl_3$): 3578, 2869, 1753, 1410 cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 7.39−7.27 (10H, m), 5.26 (1H, dt, J = 4.3, 4.3 Hz), 4.56 (1H, d, J = 12.0 Hz), 4.49 (1H, d, J = 11.1 Hz), 4.49 (2H, s), 4.06 (1H, dt, J = 4.0, 4.0 Hz), 4.03 (2H, s), 3.74 (1H, dd, J = 10.7, 4.4 Hz), 3.68 (1H, dd, J = 10.7, 5.3 Hz), 3.55 (1H, dd, J = 9.7, 4.8 Hz), 3.51 (1H, dd, J = 9.5, 5.5 Hz), 2.80 (1H, bs). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 167.5, 138.0, 137.9, 128.9, 128.4, 128.3, 128.2, 74.6, 74.0, 73.8, 71.0, 70.1, 69.3, 41.4. MS (ES+): m/z 401 $(M + Na)^+$, 379 $(M + H)^+$; found M + H 379.1312, $C_{20}H_{24}ClO_5$ requires M + H 379.1312.

(2*R*,3*R*)-1,4-Bis(benzyloxy)-2,3-butanediol Mono-*trans*-crotonate (11e). Oil. $[\alpha]_D$ = −11.5° (c = 0.4, $CHCl_3$). IR ($CHCl_3$): 2867, 1716, 1656, 1453, 1102 cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 7.36−7.27 (10H, m), 7.02 (1H, dq, J = 15.5, 6.9 Hz), 5.90 (1H, dd, J = 15.5, 1.7 Hz), 5.23 (1H, dt, J = 4.8, 4.8 Hz), 4.57 (1H, d, J = 12.0 Hz), 4.49 (2H, s), 4.49 (1H, d, J = 12.0 Hz), 4.13 (1H, m), 3.76 (1H, dd, J = 10.5, 4.7 Hz), 3.68 (1H, dd, J = 10.5, 5.0 Hz), 3.55 (1H, dd, J = 9.6, 4.6 Hz), 3.50 (1H, dd, J = 9.6, 6.3 Hz), 1.89 (3H, dd J = 6.9, 1.7 Hz). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 166.4, 146.1, 138.2, 138.1, 128.8, 128.2, 128.1, 122.5, 73.9, 73.8, 72.2, 71.3, 70.6, 69.7, 18.4. MS (CI NH_3): m/z 388 $(M + NH_4)^+$, 371 $(M + H)^+$; found M + H 371.1855, $C_{22}H_{27}O_5$ requires M + H 371.1856.

***R,R*-Diethyl Tartrate Monobenzoate (12a).**[22] Mp: 56−59 °C. $[\alpha]_D$ = +29.0° (c = 0.3, $CHCl_3$). IR ($CHCl_3$): 3534, 2982, 1738, 1602, 1452, 1371, 1301, 1108, 1071 cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 8.04 (2H, dd, J = 7.3, 0.9 Hz), 7.59 (1H, tt, J = 7.3, 0.9 Hz), 7.45 (2H, bt, J = 7.8 Hz), 5.68 (1H, d, J = 2.3 Hz), 4.87 (1H, d, J = 2.3 Hz), 4.34−4.23 (4H, m), 1.31 (3H, t, J = 7.1 Hz), 1.21 (3H, t, J = 7.1 Hz). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 170.9 (s), 166.6 (s), 165.3 (s), 133.7 (d), 130.2 (d), 130.0 (d), 128.8 (d), 128.6 (d), 73.5 (d), 70.8 (d), 62.7 (t), 62.3 (t), 14.1 (q). MS (CI NH_3): m/z 328 $(M + NH_4)^+$, 311 $(M + H)^+$, 206 $(M + H - PhC{=}O)^+$, 105 $(PhC + O)^+$. Anal. Calcd for $C_{15}H_{18}O_7$: C, 58.10; H, 5.81. Found: C, 58.24; H, 5.76.

***R,R*-Diethyl Tartrate Monocyclopropanoate (12b).** Clear oil. $[\alpha]_D$ = +19.1° (c = 0.3, $CHCl_3$). IR ($CHCl_3$): 3541, 2937, 1732, 1694, 1520, 1255 cm^{-1}. ^1H NMR ($CDCl_3$, 400 MHz): δ 5.47 (1H, d, J = 2.3 Hz), 4.75 (1H, d, J = 2.3 Hz), 4.37−4.22 (4H, m), 1.72 (1H, m), 1.31 (6H, q, J = 7.2 Hz), 1.08−1.05 (2H, m), 0.96−0.93 (2H, m). ^{13}C NMR ($CDCl_3$, 100 MHz): δ 173.5, 170.8, 166.7, 128.63, 72.8, 70.6, 62.6, 62.1, 14.1, 12.5, 9.1, 8.7. MS (CI NH_3): m/z 292 $(M + NH_4)^+$, 275 $(M + H)^+$; found M + H 275.1131, $C_{12}H_{19}O_7$ requires M + H 275.1131.

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Supporting Information Available: Figures giving NMR spectra for compounds not analyzed, **1g**,**f**, **2e**, **6e**, **8b**, **10d**, and **11b**,**d**,**e**. This material is available free of charge via the Internet at http://pubs.acs.org.

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