Regioselective and Stereoselective Methods for the Synthesis of the Pentitols

David Holland
Corporate Laboratory, Imperial Chemical Industries plc, The Heath, Runcorn WA7 4QE
J. Fraser Stoddart *
Department of Chemistry, The University, Sheffield S3 7HF

Several different approaches to the stereoselective synthesis of xylitol (1), as well as the other two pentitols, ribitol (2) and DL-arabinitol DL-(3), from the (*Z*)- and (*E*)-1-hydroxypentadienes (4) and (5) and the (*Z*)- and (*E*)-4,5-epoxypent-2-enals (6) and (7) are described. They rely upon either (*a*) epoxidations of allylic C=C double bonds followed by stereospecific (*anti*) and sometimes regioselective epoxide cleavages, or (*b*) *syn*-hydroxylations of allylic C=C double bonds. Employing approach (*a*), the (*Z*)-isomers (4) and (6) do not afford any ribitol (2) among the products and the (*E*)-isomers do not afford any xylitol (1). The consequences are reversed when approach (*b*) is adopted. The most convenient synthesis of xylitol (1) starts from the (*Z*)-isomer (6) of 4,5-epoxypent-2-enal. The formyl group in (6) is reduced, provided *acidic work-up conditions* are employed, to yield (*Z*)-(4*RS*)-4,5-epoxy-1-hydroxypent-2-ene (9), which is characterised as its acetate (10). Opening of the epoxide ring in (10) with acetate ion gives the triacetate (11), which is deacetylated to afford a key intermediate, (*Z*)-(4*RS*)-1,4,5-trihydroxypent-2-ene (12). Epoxidation of (12) with peracids (*e.g. p*-nitroperbenzoic acid) yields (t-butyl hydroperoxide with catalytically active Ti^{4+}, V^{5+}, and Mo^{6+} complexes fails) two epoxides (13) and (14), arbitrarily named isomers A (13) and B (14) subsequently shown to have the relative stereochemistries (2*S*,3*R*,4*R*) and (2*R*,3*R*,4*R*), respectively. Epoxide ring opening with acetate ion in acetic anhydride of the more abundant isomer B (14), obtained with 70% diastereoselectivity, yields xylitol penta-acetate (16) as the major product (>80% diastereoselectivity) along with small and trace amounts of the other two pentitol penta-acetates. Epoxide ring opening of isomer A with acetate ion in acetic anhydride is not a straightforward reaction for the most part and has been found to involve the intermediacy of an isolatable bicyclic orthoester (23) *en route* to some of the xylitol penta-acetate (16) formed as the principal stable product during this reaction. These variations of approach (*a*) constitute stereoselective syntheses of xylitol (1), which are claimed to be acceptable on a laboratory scale. They provide a slightly better route than an alternative one involving the transformations (4) → (33) → (34) → (39) → (16) → (1), starting from (*Z*)-1-hydroxypenta-2,4-diene (4), principally because this particular precursor is less readily accessible than (*Z*)-4,5-epoxypent-2-enal (6). By contrast, the (*E*)-isomer (5) of 1-hydroxypenta-2,5-diene is obtainable in high yield from the reduction of vinyl acrylic acid and the analogous transformations [(5) → (26) → (27) → (28) → DL-(5) → DL-(3)] provide a highly stereoselective (91%) synthetic route to DL-arabinitiol DL-(3). Osmium-catalysed *syn*-hydroxylation of (*E*)-(4*RS*)-triacetoxypent-2-ene (22), prepared from (*E*)-4,5-epoxypent-2-enal (7) in two steps [(7) → (20) → (22)], provides yet another approach to DL-arabinitol DL-(3), but the stereoselectivity (76%) of this oxidation is not as good as that observed for the epoxidation of *rel*-(3*R*,4*R*)-3,4,5-triacetoxypent-1-ene (27) in the above transformation. The synthesis of ribitol (2) by osmium-catalysed *syn*-hydroxylation of the (*Z*)-isomer (11) of (22) was achieved with a modest stereoselectivity of 66% for the oxidation step.

On account of the considerable potential commercial importance of xylitol (1) as a carbohydrate sweetener,[1] we became interested in devising synthetic routes to (1) in particular and to the other two diastereoisomeric pentitols, ribitol (2) and arabinitol (3) coincidentally (Figure 1). Xylitol (1) and ribitol (2) have [2,3] C_s symmetry and so are *meso*-compounds. Arabinitol (3) is [2,3] asymmetric and hence can exist as D- and L-enantiomers. However, with xylitol (1) as our main synthetic objective, we recognised from the outset that there was no need, in principle at least, to involve any chiral starting material or auxiliary in a stereoselective synthesis designed to afford (1) rather than ribitol (2) or DL-arabinitol DL-(3). Thus, in its conceptual form, the problem we were confronted with was one of defining relative stereochemistry and *not* absolute stereochemistry. Furthermore, it was necessary to arrange that the chiral centres at C-2 and C-4 in the pentitol constitution end up having opposite chiralities whilst at the same time ensuring that the stereochemistry at the pseudoasymmetric centre (C-3) can be expressed precisely relative to the two chiral centres in order to afford xylitol (1) with the (*r*)-configuration or ribitol (2) with the (*s*)-configuration.

Since 3-hydroxypenta-1,4-diene (divinylcarbinol) [4] and the constitutionally isomeric (*Z*)- and (*E*)-hydroxypenta-2,4-dienes (4) [5] and (5) [6] are all known compounds, we were encouraged to explore their potential as possible C_5 precursors to the pentitols. There are two obvious stereoselective pathways to examine starting from these substrates: (*a*) one involves *syn*-hydroxylation, and (*b*) the other relies upon epoxidation of the C=C double bonds followed by epoxide ring opening as a necessary adjunct wherein high regioselectivity, in addition to *anti*-stereochemistry, is desirable. We have already discussed [7] the stereoselective epoxidation of divinylcarbinol, followed by epoxide ring cleavage, as a possible synthetic approach to the pentitols in a previous paper. Contrary to earlier claims,[8] the diastereoselectivities governing the epoxide ring openings with several different reagents in both cases were not sufficiently high to constitute an attractive synthesis of xylitol (1), ribitol (2), or DL-arabinitol DL-(3). A further unappealing aspect of this approach is the absence of any configurational information in the vinylic C=C double bonds of divinylcarbinol. It is precisely because of the presence of this additional stereochemical factor in the (*Z*)-

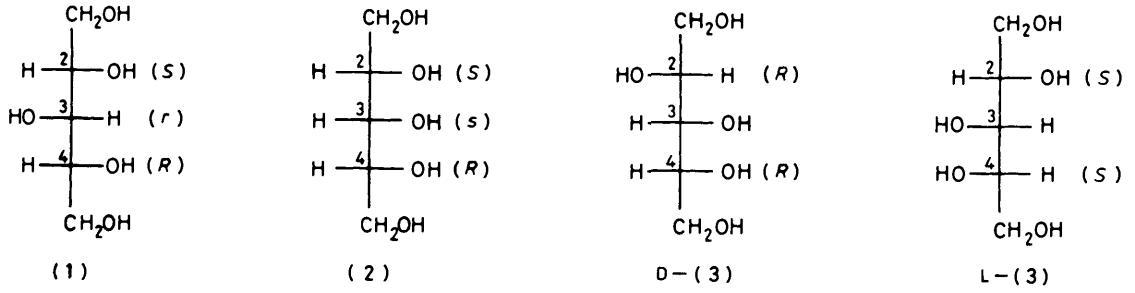
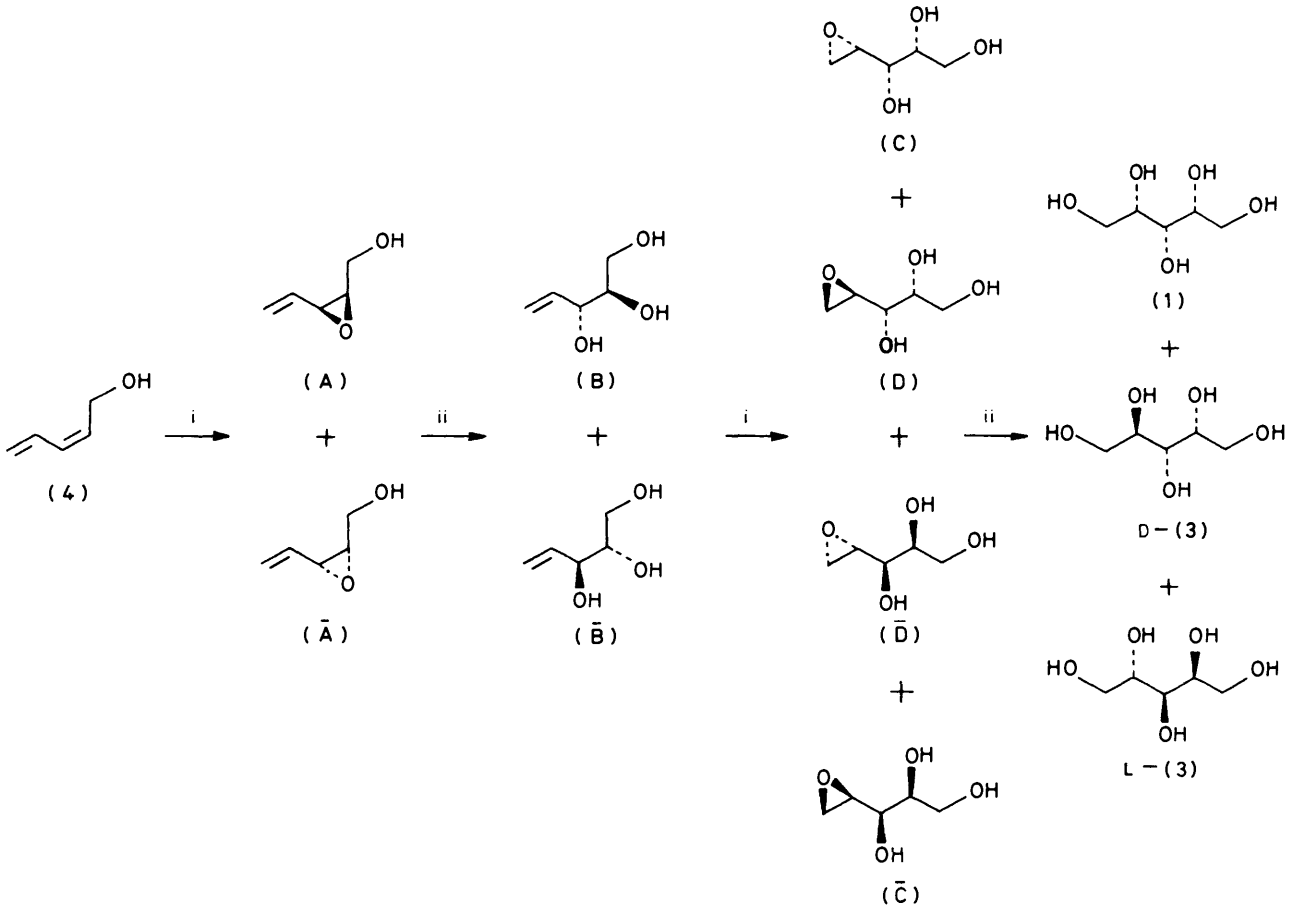


Figure 1. The pentitols and their absolute configurations



Scheme 1. *Conditions:* i, epoxidation of allylic C=C double bond; ii, epoxide cleavage

and (*E*)-1-hydroxypenta-2,4-dienes (4) and (5), where *cis*- and *trans*-geometries define respectively the configurations of one of the two C=C double bonds, that they are such attractive C_5 precursors to the pentitols. A possible sequence of events starting with the *cis*-dienol (4) and leading stereoselectivity to xylitol (1) and DL-arabinitol DL-(3) is shown in Scheme 1. It involves (*a*) epoxidation of the allylic double bond in (4) to afford the enantiomeric epoxides (A) and (Ā), (*b*) ring opening of these epoxides *at either carbon atom* to give the enantiomeric triols (B) and (B̄), (*c*) epoxidation of the terminal (allylic) double bond in the triols to produce a diastereoisomeric mixture of racemic epoxides (C), (C̄) and (D), (D̄), and (*d*) cleavage of these epoxides to yield xylitol (1), D-arabinitol D-(3), and L-arabinitol L-(3). Ribitol is *not* one of the products. By the same token, when the *trans*-dienol (5) is subjected to an identical sequence of reactions, ribitol (2), D-arabinitol D-(3), and L-arabinitol L-(3) are the expected products and *no* xylitol (1) should be formed. A consideration of the early pioneering work on the synthesis of the pentitols reveals that both Lespieau [9] and Raphael [10] made use of this kind of selectivity in their synthesis of ribitol (2) and DL-arabinitol DL-(3) from appropriate unsaturated C_5 precursors. We now report our own detailed investigations into the stereoselective synthesis of xylitol (1), ribitol (2), and DL-arabinitol DL-(3): our results have been the subject of a preliminary communication published [11] recently.

Results and Discussion

We have investigated a number of different approaches (see Figure 2) to the stereoselective synthesis of the three pentitols starting from four readily available C_5 precursors, namely the

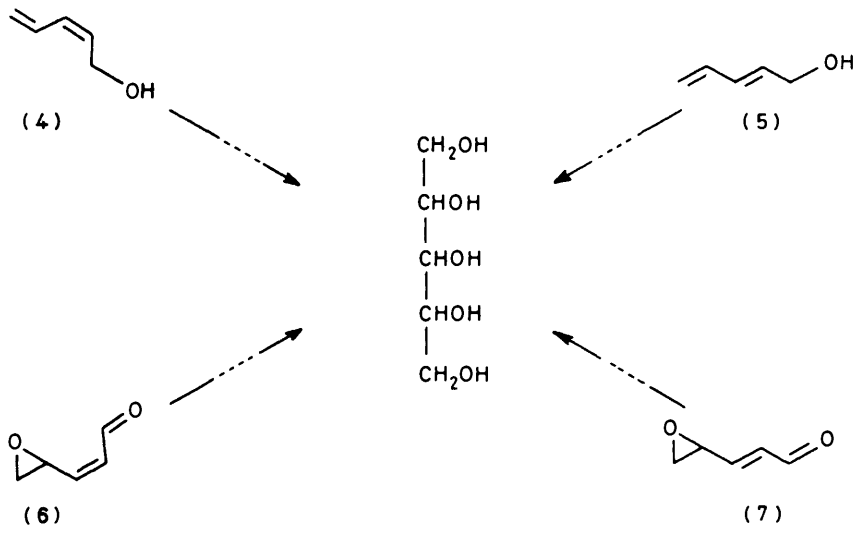
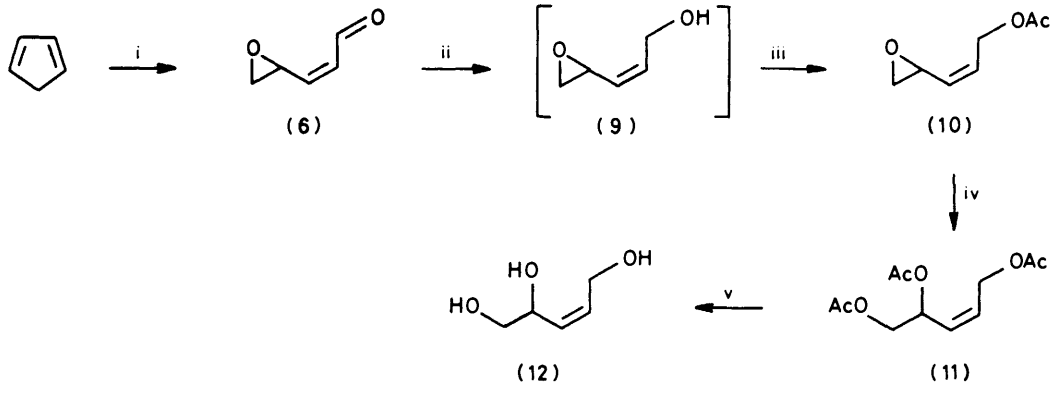


Figure 2. Some approaches to the stereoselective synthesis of the penitols

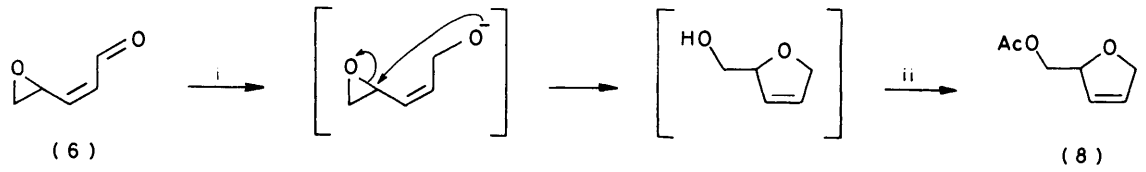


Scheme 2. *Reagents:* i, *hν*, $^1O_2$, Rose Bengal, MeOH; ii, $NaBH_4$, EtOH then H_2SO_4 to pH 5—6; iii, Ac_2O, C_5H_5H; iv, Bu^n_4NOAc, Ac_2O; v, NH_3, MeOH

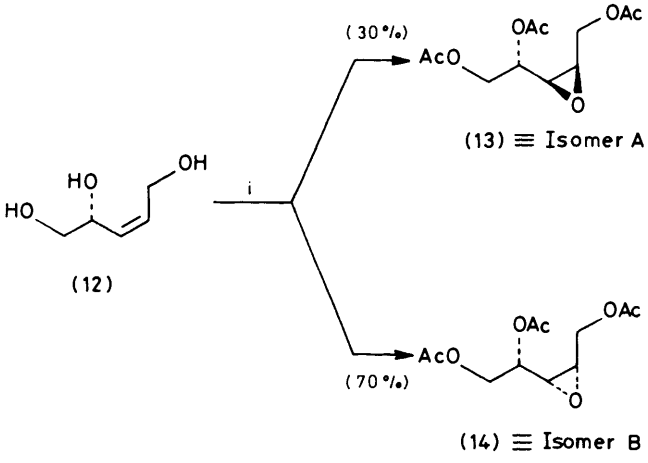
(*Z*)- and (*E*)-4,5-epoxypent-2-enals [12-14] (6) and (7), as well as the (*Z*)- and (*E*)-1-hydroxypenta-2,4-dienes [5,6] (4) and (5). We shall now discuss the different synthetic approaches we have explored from these two diastereoisomeric pairs of starting materials in the order: (6) and (7), followed by (5), and then finally (4).

From (Z)-(4RS)-4,5-*Epoxypent*-2-*enal* (6).—A novel method for preparing this epoxyaldehyde (6) from cyclopentadiene has been reported in the literature.[12-14] In our hands, photooxygenation of cyclopentadiene monomer [15] in methanol employing Rose Bengal as dye-sensitiser afforded (6) in 42% yield. Our next synthetic objective was the preparation of the *cis*-trihydroxypentene (12) from the *cis*-epoxyaldehyde (6). This was achieved (see Scheme 2) in four steps. (*a*) Chemoselective reduction of the formyl group in (6) with sodium borohydride in ethanolic solution proceeded smoothly at −40 °C to give the *cis*-hydroxyepoxypentene (9) provided the solution was acidified prior to the isolation of the product. On account of its marked instability, (9) was not characterised as such but was immediately (*b*) acetylated to afford the *cis*-acetoxyepoxypentene (10) (45%), which was then (*c*) treated with tetra-n-butylammonium acetate in acetic anhydride at 105 °C to yield the *cis*-triacetoxypentene (11) (71%). (*d*) De-*O*-acetylation of (11) in ammoniacal methanol afforded the desired *cis*-trihydroxypentene (12) in 94% yield. If acid was not added before the attempted isolation of (9), it underwent (see Scheme 3) rearrangement in part to give, presumably, 2-hydroxymethyl-2,5-dihydrofuran which was characterised as its acetate (8) along with (10) in the ratio 22 : 78, respectively. Clearly, the basic conditions, which prevail during the decomposition of ethyl borate, catalyse the intramolecular opening of the epoxide ring as shown in Scheme 3. Indeed, when the pH during the borohydride reduction of (6) was adjusted to 10—11 by addition of sodium hydroxide, *only* the rearranged product (Scheme 3), characterised again as its acetate, was isolated. During the hydrolysis of 5-hydroxy-1,2-epoxides, it is well known [16,17] that 5- and 6-membered ring ethers can be formed with the former usually predominating, particularly under alkaline conditions. The formation of 2-hydroxymethyl-2,5-dihydrofuran as shown in Scheme 3 may be regarded as an example of a favoured 5-*Exo*-*Tet* process [18] which can be described more precisely as an *exo* : 1,5 O−C:O:3 eliminative ring fission according to the system of nomenclature advocated by Stirling.[17] There are many examples of *exo* : 1,*n* O−C:O processes [17] in carbohydrate chemistry.[16,19]

Epoxidation of the *cis*-trihydroxypentene (12) with *p*-nitroperbenzoic acid in tetrahydrofuran (THF), followed by acetylation of the products, should give rise to two diastereoisomeric triacetoxy-3,4-epoxypentenes (13) and (14) as shown



Scheme 3. *Reagents:* i, $NaBH_4$, EtOH then NaOH; ii, Ac_2O, C_5H_5N



Scheme 4. *Reagents:* i, PNPBA, THF then Ac_2O, C_5H_5N

in Scheme 4. In fact, g.l.c. analysis indicated that two products were present after this sequence of reactions: the major product had the shorter elution time and the ratio of the peak areas was *ca.* 7 : 3. The diastereoisomeric mixture (13) and (14) was heated at 110 °C with a catalytic amount of tetra-n-butylammonium acetate in acetic anhydride. The reaction was followed by g.l.c. After 16 hours, the two peaks corresponding to the starting materials could no longer be detected and were replaced by another two peaks with much longer retention times but with similar relative intensities of 76 : 24. The minor product had the shorter retention time and was shown to be identical with an authentic sample of DL-arabinitol penta-acetate DL-(15). The major product with the longer retention time was shown to be identical with an authentic sample of xylitol penta-acetate (16). The mixture of penta-acetates was separated by column chromatography and xylitol penta-acetate (16) was (*a*) characterised as a crystalline compound and was (*b*) converted after hydrolysis into xylitol (1), which was also characterised as a crystalline compound. The fact that the relative concentrations (76 : 24) of the penta-acetates were almost identical with the relative concentrations (*ca.* 7 : 3) of the diastereoisomeric triacetoxy-3,4-epoxypentanes suggests that nucleophilic attack by acetate ion on the epoxide rings of (13) and (14) might be occurring with high regioselectivity and that the major diastereoisomer is being converted exclusively into xylitol penta-acetate (16) and the minor diastereoisomer exclusively into DL-arabinitol penta-acetate DL-(15). However, numerous examples in the literature [16,17] on the ring opening of epoxides with a variety of nucleophiles indicate that this interpretation is potentially naive and could therefore be totally misleading. Moreover, the presence of acetoxy groups in (13) and (14), which could participate in epoxide cleavage,[16,19] must also be recognised. Thus, we were encouraged to separate and isolate the pure diastereoisomers (13) and (14) and to investigate their reactions individually with tetra-n-butylammonium acetate in acetic anhydride. The isomeric triacetoxy-3,4-epoxypentanes (13) and (14) were

Table 1. The composition of products formed by epoxide cleavage of isomers A (13) and B (14) at 121 °C

			Product composition (%)		
Substrate	Solvent	Reagent	DL-Ara-$(OAc)_5$ DL-(15)	Xyl-$(OAc)_5$ (16)	Rib-$(OAc)_5$ (17)
Isomer A (13)	Ac_2O	Bu^n_4NOAc (5 mol %)	35	65	
Isomer A (13)	Ac_2O		36	64	
Isomer B (14)	Ac_2O	Bu^n_4NOAc (5 mol %)	15	82	3
Isomer B (14)	Ac_2O		10	88	2

separated by h.p.l.c. The first and minor component eluted from the column was designated as isomer A; the second and major component eluted from the column was designated as isomer B. Unfortunately, it was not possible to assign relative configurations with any confidence to isomers A and B on the basis (*cf.* ref. 7) of their high resolution ^1H n.m.r. spectra.[20] The fact that the vicinal coupling constants for $J_{2,3}$ of 8.1 Hz in (13) and of 8.3 Hz in (14) are so similar argues strongly against attempting to make an assignment of relative configurations to the chiral centres at C-2 and C-3 in the isomeric triacetoxy-3,4-epoxypentanes. It was decided, therefore, to investigate the consequences of epoxide cleavage in isomers A and B by heating them with acetic anhydride at 121 °C in both the presence and absence of added acetate ion. The results obtained after the reactions had gone to completion in these four separate experiments are summarised in Table 1. It is obvious from a cursory inspection of these data that epoxide ring opening is *not* highly regioselective in the case of either isomer A or isomer B, since both afford mixtures of the two penta-acetates (15) and (16) with, respectively, the *arabino*- and *xylo*-configurations, expected on the basis of stereospecific *trans*-opening of the epoxide rings. However, it is interesting that xylitol penta-acetate (16) is the major product formed from both diastereoisomeric triacetoxy-3,4-epoxypentanes (13) and (14). Ribitol penta-acetate (17), which is observed (see Table 1) as a very minor component of the products from isomer B, must be the result either of (*a*) non-stereospecific epoxide ring opening or, more probably, of (*b*) acetoxy group participation [16,21] during the epoxide cleavage. An analysis of samples of the reaction mixtures by g.l.c. at intervals of *ca.* 1 hour during the reactions of isomer A with acetic anhydride with and without added tetra-n-butylammonium acetate revealed some unexpected reaction behaviour. Representative chromatographic traces obtained from the reaction mixtures after 1, 4, and 23 hours are shown in Figure 3. During the early stages (see Figure 3a) of the reaction, DL-arabinitol penta-acetate DL-(15) is the major product. However, by the time (see Figure 3c) most of the starting material (isomer A) had been consumed, xylitol penta-acetate (16) had become the major product of the reaction. The product compositions for the reactions of isomers A and B are shown as functions of time in Figure 4. It is clear from

this Figure that it is only isomer A which exhibits this atypical reaction behaviour; in the case of the reaction of isomer B, the major product at all stages during the reaction is xylitol penta-acetate (16), although the minor product, DL-arabinitol penta-acetate DL-(15), is accompanied by trace amounts of ribitol penta-acetate (17). Another surprising observation in the case of the reaction of isomer A was the *increase* (see Figure 3) in the relative peak area of the starting material during the first few hours of the reaction. When the area of this peak relative to that of an internal standard was plotted against the reaction time, the result was that shown in Figure 5. The somewhat unusual reactivity exhibited by isomer A can be rationalised if it is assumed that this triacetoxy-3,4-epoxypentane reacts simultaneously by three different reaction pathways. Two of these reaction pathways can presumably be associated with nucleophilic attack by acetate ion at C-3 or C-4 of the oxiran ring. The third pathway involves the production of an intermediate which will be referred to at this juncture as compound (Z). This intermediate must satisfy two conditions. (*a*) It must have a retention time on the Silicone OV17 column [7] identical with that observed for isomer A. (*b*) It must react to give xylitol penta-acetate (16) as the major product under the reaction conditions which lead to its formation from isomer A. If it is assumed that isomer A has the *ribo*-configuration associated with its three chiral centres, *i.e.* it is compound (13), then a possible reaction pathway, which could lead to the accumulation of an intermediate terminal epoxide (18) that would subsequently undergo nucleophilic attack by acetate ion regioselectivity at the primary carbon atom of the oxiran ring to give xylitol penta-acetate (16) as the major product, is the one shown in Scheme 5. However, although the terminal epoxide (18) might be expected to be the more stable epoxide thermodynamically, it would also be expected to be more susceptible to nucleophilic attack by acetate ion than isomer A (13). Hence, it would be surprising if (18) corresponded to the intermediate, compound (Z). Nonetheless, the hypothesis was put to the test. The terminal epoxide (18) was available as one component of an approximately equimolar mixture of the two diastereoisomeric epoxides (18) and (19). This mixture was prepared from the *cis*-epoxyaldehyde (6) by the route shown in Schemes 6 and 7. Treatment of (6) with a solution of triphenylphosphine in benzene catalyses [12] its isomerisation to the *trans*-isomer (7). Chemoselective reduction of the formyl group in (7) with sodium borohydride in ethanolic solution at −30 °C afforded

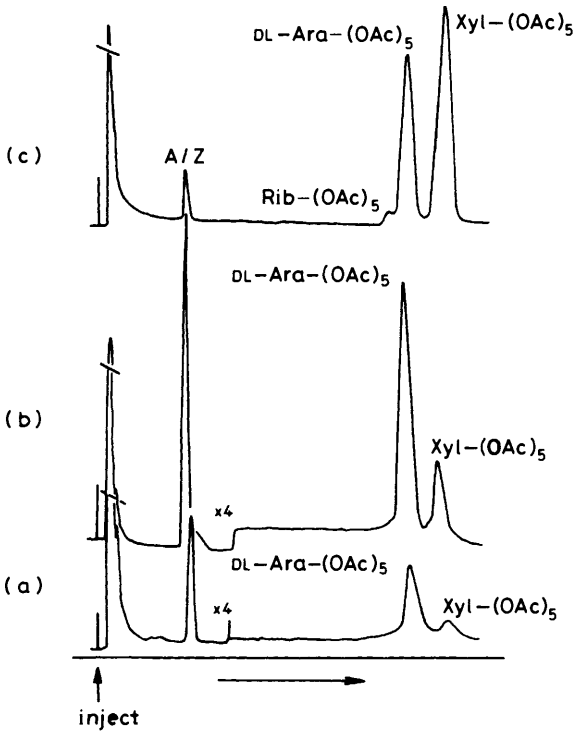


Figure 3. Chromatographic traces after (a) 1 h, (b) 4 h, and (c) 23 h of the reaction of isomer A (13) with tetra-n-butylammonium acetate in acetic anhydride at 121 °C

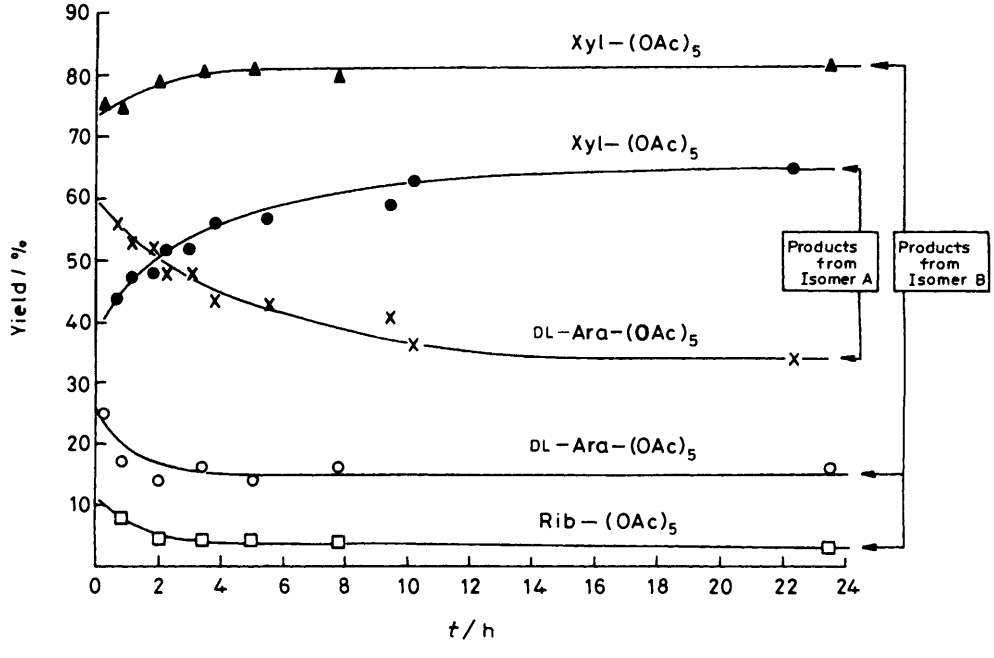


Figure 4. Percentages of penta-acetates formed against time for the reactions of isomers A (13) and B (14) with tetra-n-butylammonium acetate in acetic anhydride at 121 °C

a product which we assume contains the *trans*-hydroxyepoxypentene (20). This compound was not isolated. The crude product of the reduction was acetylated to give a mixture of the *trans*-acetoxyepoxypentene (21) and the *trans*-triacetoxypentene (22), derived presumably from (21) by opening of the oxiran ring during the acetylation of (20). The compounds were separated by m.p.l.c. to yield 20 and 7% respectively of (21) and (22). Catalytic hydroxylation [22] of (21), followed by acetylation, afforded (see Scheme 7 and Table 2) an equimolar mixture of the diastereoisomeric terminal epoxides (18) and (19). Now, the reaction mechanism proposed in Scheme 5 could be tested experimentally. Isomer A (13) was treated with tetra-n-butylammonium acetate in acetic anhydride at 112 °C. The reaction was followed by g.l.c., and when 4 hours had elapsed, a mixture of (18) and (19) was added to the reaction mixture. G.l.c. analysis revealed the presence of two additional peaks for (18) and (19) flanking the single unresolved peak corresponding to isomer A (13) and compound (Z). Thus, compound (Z) is not the terminal epoxide (18). It was now

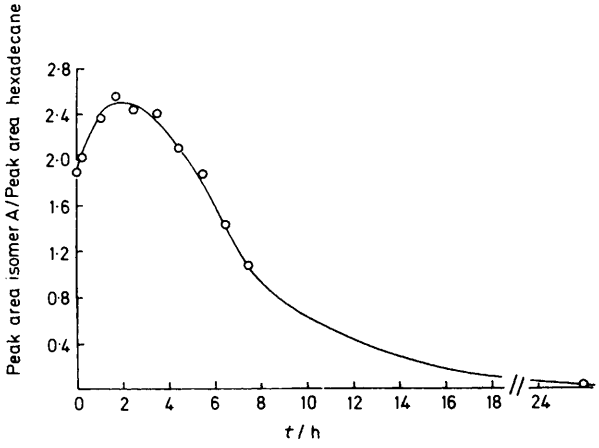
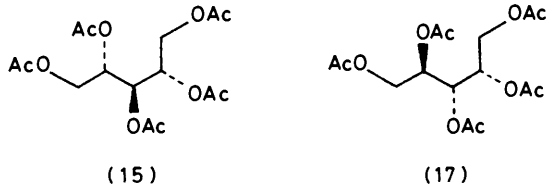


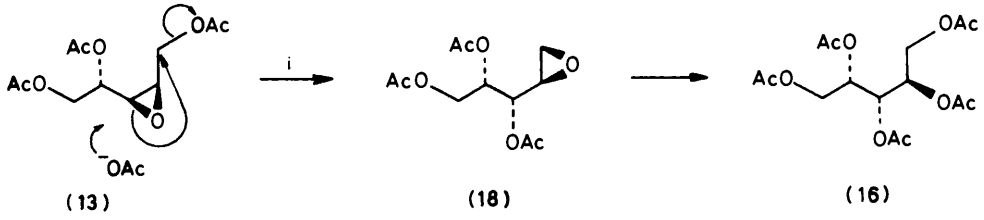
Figure 5. A plot *versus* time of the chromatographic peak area relative to the internal standard (hexadecane) of the peak corresponding to the elution time of isomer A (13) during its reaction with tetra-n-butylammonium acetate in acetic anhydride at 121 °C

Table 2. The composition of products prepared [a] from the 'diols' obtained by *syn*-hydroxylation of the *cis*-olefins (10)—(12) and the *trans*-olefins (21), (22), and (25)

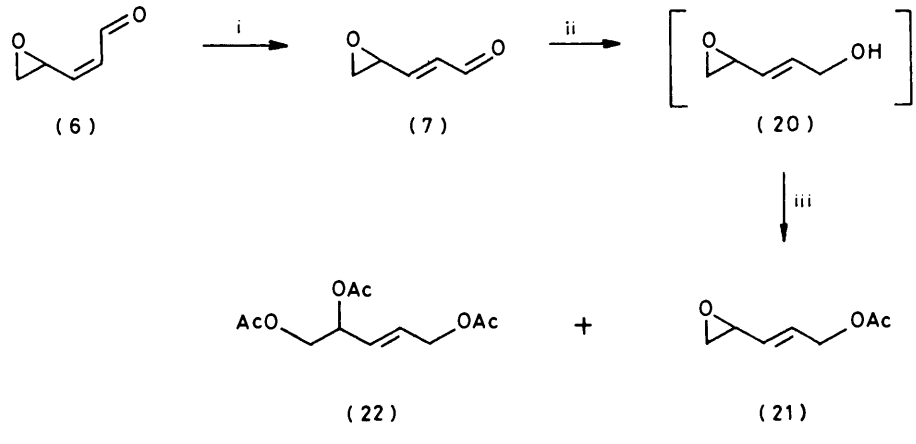
Olefin	Reaction [b] time (h)	Product composition (%) DL-Ara-(OAc)$_5$ DL-(15)	Xyl-(OAc)$_5$ (16)	Rib-(OAc)$_5$ (17)
(11)	66	28	6	66
(12)	16	46	3	51
(10)	16	46	2	52
(22)	113	73	24	2
(25)	16	63	37	0
(21)	16	51	49	0

[a] For compounds (11), (12), (22), and (25), *syn*-hydroxylation is followed by acetylation; for compounds (10) and (21), *syn*-hydroxylation and acetylation are followed by epoxide cleavage with acetate ion in acetic anhydride. [b] Refers to osmium-catalysed *syn*-hydroxylation.

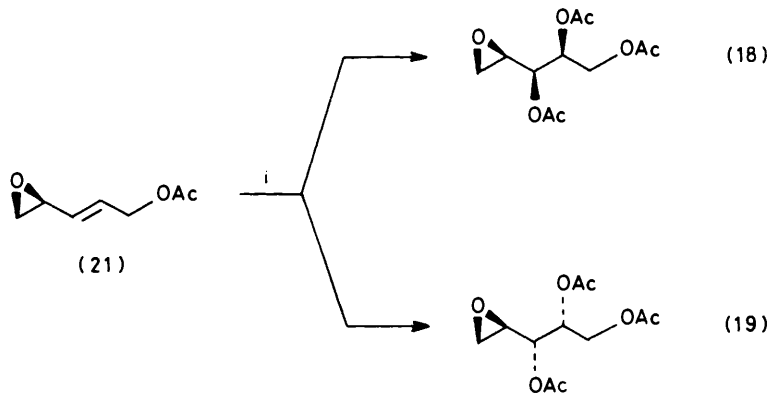




Scheme 5. *Reagents:* i, Bu^n_4NOAc, Ac_2O



Scheme 6. *Reagents:* i, Ph_3P, C_6H_6; ii, $NaBH_4$, EtOH; iii, Ac_2O, C_5H_5N



Scheme 7. *Reagents:* i, Bu^tO_2H, OsO_4, Et_4NOAc, Bu^tOH, Me_2CO followed by Ac_2O, C_5H_5N

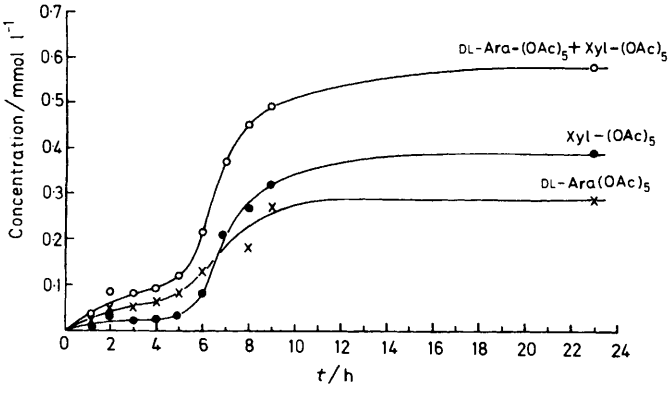


Figure 6. A plot of concentration *versus* time for the conversion of isomer A (13) during its reaction with tetra-n-butylammonium acetate in acetic anhydride at 112 °C into DL-arabinitol penta-acetate DL-(15) and xylitol penta-acetate (16)

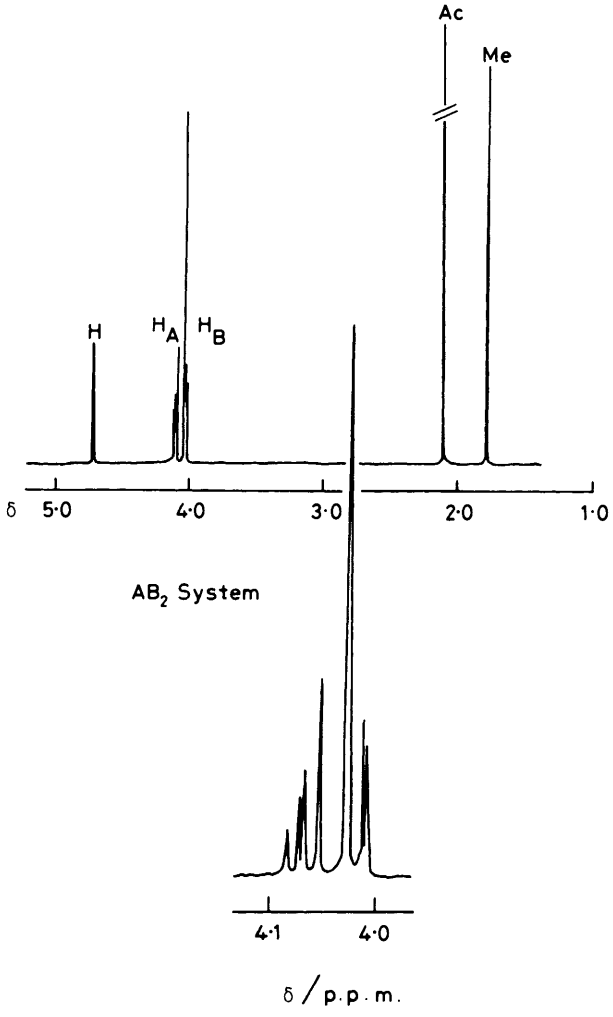
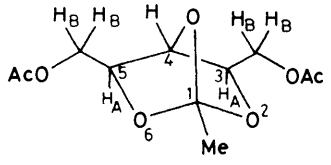


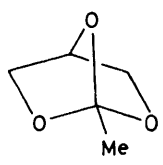
Figure 7. The high resolution (400 MHz) ^1H n.m.r. spectrum in deuteriochloroform of the bicyclic orthoester (23) which corresponds to compound (Z)

apparent that compound (Z) had to be isolated and characterised.

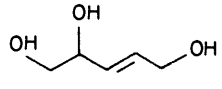
A preliminary experiment was carried out in which isomer A (13) was treated with tetra-n-butylammonium acetate in acetic anhydride at 112 °C and the relative concentrations of xylitol penta-acetate (16) were measured at 2-hourly intervals by g.l.c. The S-shaped concentration–time curve (Figure 6) is not only characteristic of a consecutive reaction, *i.e.* (13) ⟶ compound (Z) ⟶ (16), but also indicates that the intermediate [compound (Z)] had reached its highest concentration after the reaction had been running for *ca.* 5 hours. Identical experimental conditions were employed during a larger scale reaction which was quenched by cooling the reaction mixture to room temperature after 5 hours at 112 °C. On addition of ethyl acetate–light petroleum (b.p. 60—80 °C) (3 : 7) to the crude reaction product remaining after evaporation of acetic anhydride, a white crystalline solid precipitated. It was isolated and stored under nitrogen in the presence of solid carbon dioxide. G.l.c. analysis indicated it to have a retention time corresponding to that of compound (Z). Moreover, when this crystalline material was heated in acetic anhydride at 112 °C, the major product (>98% diastereoselectivity) was xylitol penta-acetate (16). Elemental analysis revealed that the empirical formula is $C_{11}H_{16}O_7$, supporting the view that compound (Z) is constitutionally isomeric with isomer A. The high resolution (400 MHz) ^1H n.m.r. spectrum of compound (Z) in deuteriochloroform is reproduced in Figure 7. On the basis of this spectral evidence, the structure of compound (Z) is proposed to be that of a bicyclic orthoester (23) which is closely related to the previously reported [23] glycerol analogue (24). The singlet at δ 4.71 may be assigned to the bridgehead proton. The torsional angles relating this proton to the two vicinal protons H_A are *ca.* 90° and so the absence of a vicinal coupling constant is not surprising.[24] The seven-line multiplet



(23)

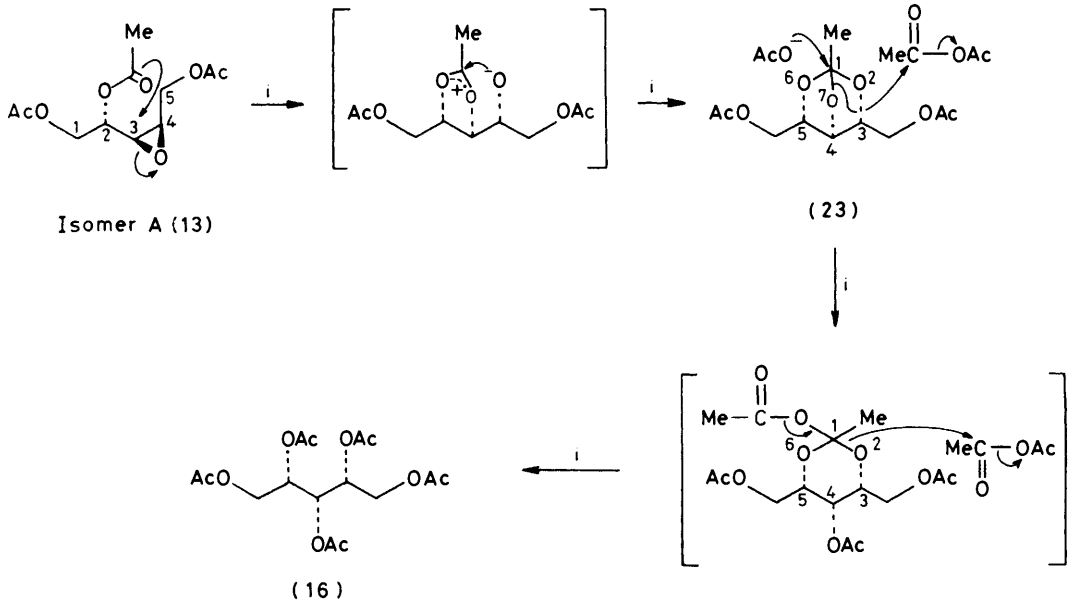


(24)



(25)

conditions. (*a*) There must be complete retention (or inversion, which is most unlikely) of the configurations of the three stereogenic centres in the bicyclic orthoester (23). (*b*) The formation if xylitol penta-acetate (16) from (23) must occur more slowly than the formation of (23) from isomer A (13). The bicyclic orthoester (23) possesses a strongly electrophilic centre at the bridgehead carbon atom (C-1). Thus, nucleophilic attack at this carbon atom by acetate ion leads to an intermediate in which the configuration is retained at the other bridgehead carbon atom (C-4). The cyclic intermediate is then expected to react with acetic anhydride (see Scheme 8) in such a way that only xylitol penta-acetate (16) is formed as



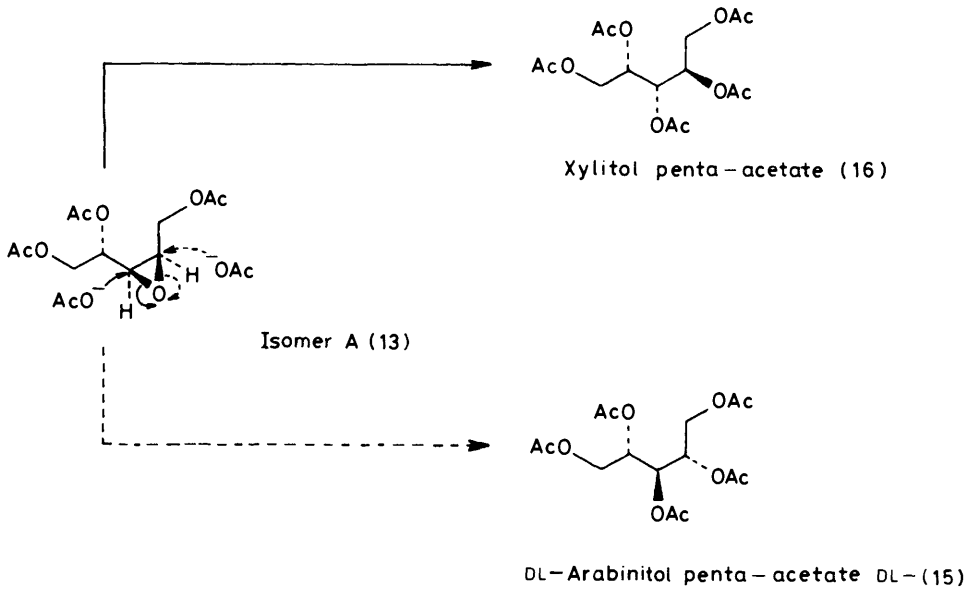
Isomer A (13)

(23)

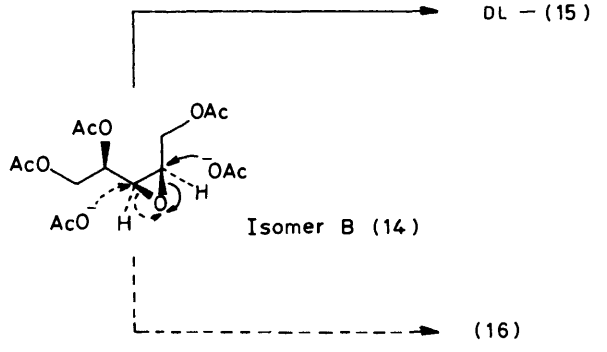
(16)

Scheme 8. *Reagents:* i, Bu^n_4NOAc, Ac_2O

observed in the region δ 4.08—4.02 integrates for six protons and constitutes a classic AB_2 system with J_{AB} 6.5 Hz for the C_s symmetry-related methine protons (H_A) and methylene groups in which the diastereoisotopic protons (H_B) are clearly giving rise to an isochronous signal. The two high-field singlets at δ 2.10 and 1.78, integrating for six and three protons respectively, may be assigned to the enantiotopic acetoxy groups and the bridgehead methyl group in (23). The assignment of the bicyclic orthoester structure to compound (Z) allows us to propose a mechanism (see Scheme 8) by which isomer A (13), assuming it has the *ribo*-configuration, might be converted into (23) in the presence of acetate ion in acetic anhydride solution. The *ribo*-configuration facilitates the participation of the acetoxy group at C-2 in the intramolecular displacement at C-3 leading to opening of the oxiran ring in (13). A local *erythro*-relationship, such as that between C-2 and C-3, has been noted previously by Buchanan and Edgar [25] to favour participation in acyclic systems. In general, neighbouring group participations of this type are well documented in carbohydrate chemistry.[16,19,21] The acetoxy-assisted oxiran ring opening of (13) generates a dipolar intermediate which leads directly to the stable bicyclic orthoester (23). It will be recalled that when (23) is subjected for a prolonged time to the same reaction conditions as those employed during its formation from isomer A (13), then it is converted stereoselectivity into xylitol penta-acetate (16). Thus, a mechanistic proposal for this reaction must satisfy two a result of retention of configuration at both C-3 and C-5. The intramolecular collapse of the dipolar intermediate to give the bicyclic orthoester (23) is obviously, as expected, a much more favourable reaction than is the intermolecular breakdown of (23) to give xylitol penta-acetate (16). The mechanistic steps, summarised in Scheme 8, depend upon the assignment of the *ribo*-configuration to isomer A (13) and, hence, an *arabino*-configuration to isomer B (14). The major products of the reactions of both these isomers with catalytic amounts of tetra-n-butylammonium acetate in acetic anhydride can be rationalised (see Schemes 9 and 10) in terms of these relative configurational assignments. Thus, non-participative opening of the oxiran ring of isomer A (13) with acetate ion affords (Scheme 9) xylitol penta-acetate (16) if C-3 is attacked and DL-arabinitol penta-acetate DL-(15) if C-4 is attacked. Likewise, non-participative opening of the oxiran ring of isomer B (14) with acetate ion affords (Scheme 10) DL-arabinitol penta-acetate DL-(15) if C-3 is attacked and xylitol penta-acetate (16) if C-4 is attacked. Although the trace amounts of ribitol penta-acetate (17) obtained (Table 1) from isomer B (14) probably result from participation by one or more of the acetoxy groups during opening of the oxiran ring, we cannot be precise mechanistically about the nature of this side reaction. The product compositions listed in Table 1 indicate that isomer B (14) provides a more highly stereoselective route to xylitol penta-acetate (16) than does isomer A (13). However, if isomer A (13) could be converted more efficiently into the



Scheme 9.



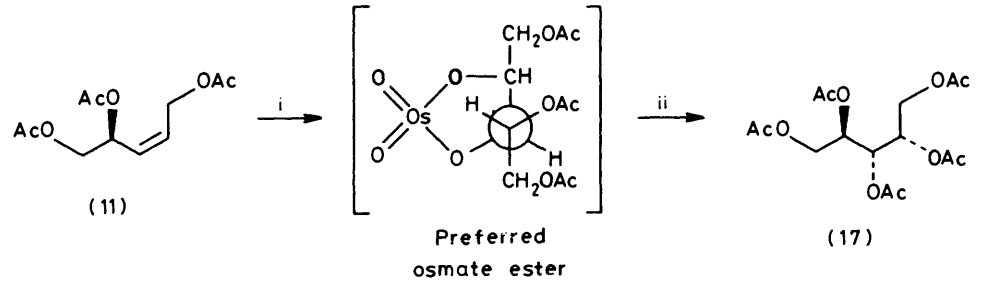
Scheme 10.

bicyclic orthoester (23), then a highly stereoselective route to xylitol penta-acetate (16) would result. Alas, optimisation of approaches to the stereoselective synthesis of (16) from either isomer A (13) or B (14) also requires an efficient separation procedure for this isomeric mixture. To date, this has not been established and so a stereoselective synthesis of xylitol penta-acetate (16) from the isomeric *mixture* of (13) and (14) has been developed as a compromise solution. When a mixture of isomer A (13) and B (14) was treated with a solution of tetra-n-butylammonium acetate in acetic anhydride at 112 °C, a mixture of penitol penta-acetates was obtained in 63% yield and xylitol penta-acetate (16) constituted 76% of these products. Column chromatography afforded xylitol penta-acetate (16) as a crystalline compound in 21% yield. Deacetylation of (16) led to the isolation (27% yield) of a crystalline sample of xylitol (1).

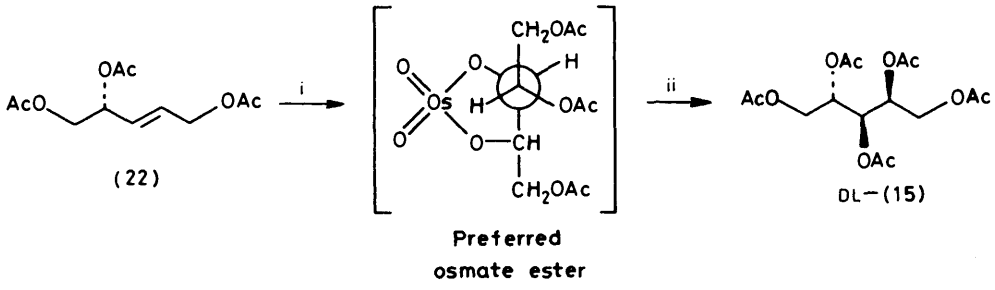
The stereoselective synthesis of xylitol (1) from (*Z*)-(4*RS*)-4,5-epoxypent-2-enal (6) outlined above might also be improved by employing a more diastereoselective epoxidising reagent on the *cis*-trihydroxypentene (12). Thus, (12) was treated with a range of different epoxidising reagents. These included t-butyl hydroperoxide with catalytically active Ti^{4+},V^{5+}, or Mo^{6+} complexes which have been shown [20,26-33] to be highly diastereoselective in the epoxidations of acyclic secondary allylic alcohols. Alas, the *cis*-trihydroxypentene (12) was not epoxidised under a wide range of reaction conditions by any of these reagents derived from titanium tetraisopropoxide, vanadyl bis(acetylacetonate), and molybdenum dioxybis(acetylacetonate). Our investigations have revealed other examples (see ref. 7 and later in the Discussion section) of polyhydroxyolefins which are not epoxidised by these reagents. It is possible that if more than one of the hydroxy groups in the substrate becomes co-ordinated to the metal, then binding of the t-butyl hydroperoxide to the metal will be prevented and so reaction will not ensue and a catalytic cycle [26] will not be established. The *cis*-trihydroxypentene (12) was also treated with the catalytic epoxidising reagent [34] prepared *in situ* from hydrogen peroxide and a small quantity of hexafluoroacetone sesquihydrate; again, (12) was not epoxidised by this reagent. Attempts to epoxidise the *cis*-triacetoxypentene (11) with these reagents also failed.

Our investigations show that a highly stereoselective synthesis of xylitol (1) from (*Z*)-(4*RS*)-4,5-epoxypent-2-enal (6) is feasible. However, there is a need to develop an inexpensive epoxidising reagent capable of exhibiting good diastereoselectivity towards either the *cis*-triacetoxypentene (11) or the *cis*-trihydroxypentene (12).

A 1,2-diol unit prepared from an epoxide formed from a *cis*-olefin has the *threo*-configuration as a consequence of the *anti*-stereospecificity characterising the effective hydroxylation. Conversely, stereospecific *syn*-hydroxylation of a *cis*-olefin should result in an *erythro*-configuration for the newly created 1,2-diol unit. Thus, *syn*-hydroxylation of *cis*-olefins, such as (11) and (12), should lead stereospecifically to pentitol derivatives with the DL-*arabino*- and *ribo*-configurations. Moreover, a stereoselective synthesis leading preferably to one of the two pentitol configurations would result, if the chiral centre at C-4 in (11) and (12) influenced significantly the direction of approach of the *syn*-hydroxylating reagent, to the diastereotopic faces of the C=C double bond. Samples of (11) and (12) were treated with the catalytic hydroxylating reagent prepared from osmium tetraoxide and an aqueous solution of t-butyl hydroperoxide according to the procedure developed by Sharpless.[22] After acetylation of the products, g.l.c. analysis revealed the product compositions shown in Table 2. A sample of the *cis*-acetoxyepoxypentene (10) was also (*a*) treated with the Sharpless hydroxylating reagent at 60 °C, and then (*b*) the diols acetylated, and (*c*) the epoxide



Scheme 11. *Reagents:* i, Bu^tO_2H, OsO_4, Et_4NOAc, Bu^tOH, Me_2CO; ii, Ac_2O, C_5H_5N

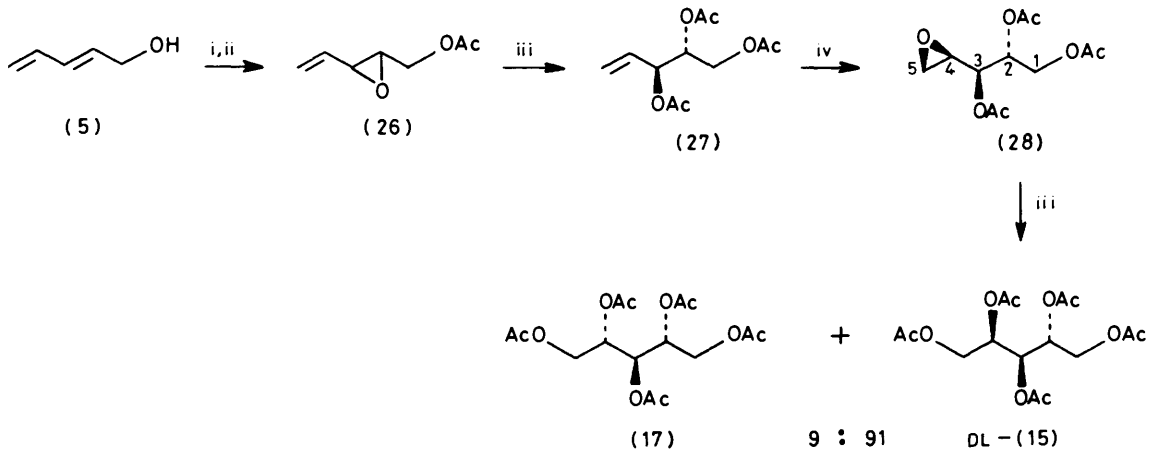


Scheme 12. *Reagents:* i, Bu^tO_2H, OsO_4, Et_4NOAc, Bu^tOH, Me_2CO; ii, Ac_2O, C_5H_5N

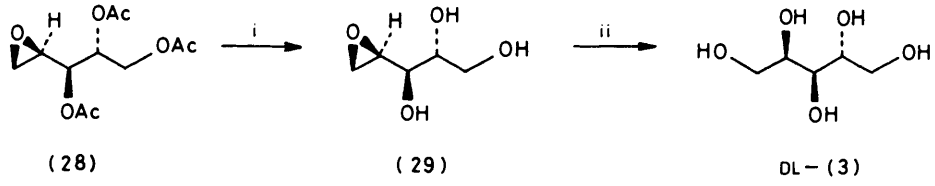
rings opened with acetate ion in acetic anhydride. The ratio of penta-acetates indicated by g.l.c. analysis is recorded in Table 2. The results in this Table reveal that (*a*) the penta-acetates DL-(15) and (17) with the DL-*arabino*- and *ribo*-configurations, respectively, are the stereospecific products as expected, and (*b*) that modest stereoselectivity for ribitol penta-acetate (17) is observed especially in the case of the *cis*-triacetoxypentene (11). Scheme 11 shows that, if steric effects associated with the acetoxy group at C-4 are dominant during formation of the intermediate osmate ester, then ribitol penta-acetate (17) should be the stereoselectively preferred diastereoisomer, in accordance with observation (see Table 2). The fact that the diastereoselectivity is considerably less in the case of the *cis*-trihydroxypentene (12) and the *cis*-acetoxyepoxypentene (10) lends support to this interpretation of the results. On the basis of these experiments, a stereoselective synthesis of ribitol (2) was developed by treating (11) with the Sharpless hydroxylating reagent at 50 °C for 19 hours. After a reaction sequence involving (*a*) acetylation, (*b*) chromatography, and (*c*) deacetylation, ribitol (2) was isolated as a crystalline compound.

From (E)-(4RS)-4,5-*Epoxypent*-2-*enal* (7).—A 1,2-diol unit with a *threo*-configuration can be obtained as a result of a stereospecific *syn*-hydroxylation of a *trans*-olefin. Thus, *syn*-hydroxylation of *trans*-olefins such as (21) and (22) should lead stereospecifically to pentitol derivatives with DL-*arabino*- and *xylo*-configurations. The preparation of the *trans*-acetoxypentene (21) and the *trans*-triacetoxypentene (22) has been discussed in the previous section and is summarised in Scheme 6. (*E*)-(4*RS*)-4,5-Trihydroxypent-2-ene (25) was obtained on deacetylation of (22). Table 2 records the results obtained on treating samples of (21), (22), and (25) with the Sharpless hydroxylating reagent and converting the products into mixtures of the pentitol penta-acetates. As expected, the penta-acetates DL-(15) and (16) with the DL-*arabino*- and *xylo*-configurations, respectively, are the stereospecific products. The diastereoselectivity for DL-arabinitol penta-acetate DL-(15), which again is most evident with the *trans*-triacetoxypentene (22), can be rationalised (see Scheme 12) on steric grounds as in the case of the *cis*-isomer (11) (*cf.* Scheme 11). On the basis of these experiments, a stereoselective synthesis of DL-arabinitol DL-(3) was developed by treating (22) with the Sharpless hydroxylating reagent at 50 °C for 19 hours. Acetylation of the crude diols afforded a product from which DL-arabinitol penta-acetate DL-(15) separated on fractional crystallisation from methanol. Deacetylation of DL-(15) gave DL-arabinitol DL-(3) as a crystalline compound.

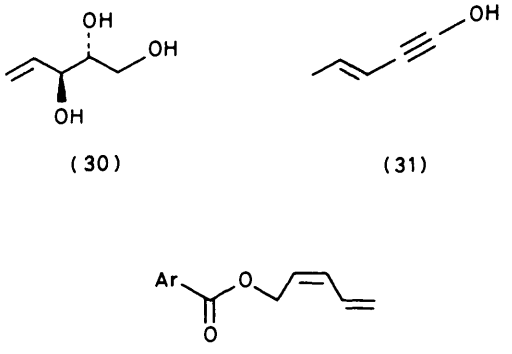
From (E)-1-*Hydroxypenta*-2,4-*diene* (5).—An even more highly selective stereoselective synthesis of DL-arabinitol penta-acetate DL-(15) has been devised (see Scheme 13) from the *trans*-1-hydroxypenta-2,4-diene (5). Treatment of (5) in dichloromethane with an epoxidising reagent prepared from t-butyl hydroperoxide and a catalytic amount of vanadyl acetylacetonate led to a completely regioselective reaction in which *only* the allylic double bond was epoxidised to give the acetoxyepoxypentene (26) after acetylation of the reaction mixture. Opening of the oxiran ring in (26) with tetra-n-butylammonium acetate in acetic anhydride afforded the triacetoxypentene (27), the terminal C=C double bond of which proved extremely difficult to epoxidise. Eventually, epoxidation was effected with buffered trifluoroperoxyacetic acid in dichloromethane to yield only one of the two possible diastereoisomeric products. On the basis of its further reactivity, we believe that the diastereoisomer which is obtained with extremely high stereoselectivity has the *arabino*-configuration characterising its three chiral centres, *i.e.* it is represented by formula (28) in Scheme 13. When this triacetoxyepoxypentane is treated with tetra-n-butylammonium acetate in acetic anhydride, DL-arabinitol penta-acetate DL-(15), which would ensue from attack by the acetate ion at C-5 [the primary position in (28)], is by far (91% selectivity) the major product with ribitol penta-acetate (17), resulting from attack by the acetate ion at C-4 [the secondary position in (28)], present as the minor constituent. Since this assessment of the oxiran ring opening of (28) by acetate ion depends on the lack of participation of the neighbouring acetoxy groups



Scheme 13. *Reagents:* i, $VO(acac)_2$, Bu^tO_2H, PhMe; ii, Ac_2O, C_5H_5N; iii, Bu_4^nNOAc, Ac_2O; iv, CF_3CO_3H, Na_2HPO_4, CH_2Cl_2



Scheme 14. *Reagents:* i, NH_3, MeOH; ii, H_2SO_4, H_2O



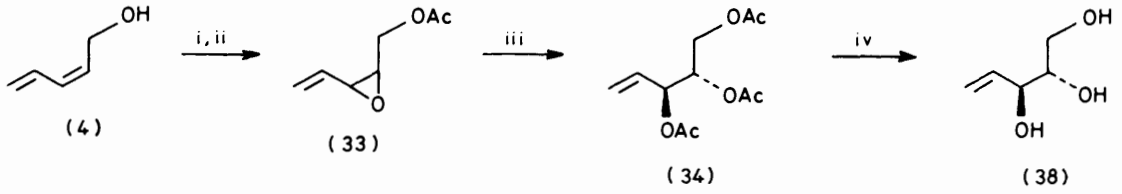
in the triacetoxyepoxypentane, it was decided to deacetylate (see Scheme 14) and examine the opening of the oxiran ring in the derived trihydroxyepoxypentane (29) under acidic conditions where (*a*) neighbouring group participation would be most unlikely, and (*b*) ring opening would be expected to occur with high regioselectivity at the primary position. When this sequence of reactions was performed on (28), DL-arabinitol penta-acetate DL-(15) was the only isomer isolated from the acetylated reaction mixture. Thus, we conclude that (29), and hence (28), have the *arabino*-configuration. One major problem remains in relation to a stereoselective synthesis of DL-arabinitol DL-(3) according to Scheme 13; the highly diastereoselective epoxidation of the terminal C=C double bond in (27) could only be achieved in very low yields (6%) with excess of a highly electrophilic reagent. Since no other epoxidising reagent could be found which would effect the transformation (27) ⟶ (28), let alone improve upon the yield obtained with trifluoroperoxyacetic acid, it was decided to examine the epoxidation of the 3,4,5-trihydroxypent-1-ene (30) obtained on deacetylation of (27). The results summarised in Table 3 reveal that, although reactivity of (30) was better towards peracids, diastereoselectivity was sacrificed to an unacceptable extent.

Table 3. The composition of the products obtained [a] from *rel*-(3*R*,4*R*)-3,4,5-trihydroxypent-1-ene (30) on epoxidation

		Product composition (%)	
Substrate	Reagent	DL-Ara-(OAc)$_5$ DL-(15)	Rib-(OAc)$_5$ (17)
(30)	p-$O_2NC_6H_4CO_3H$	55	45
(30)	CF_3CO_3H	70	30

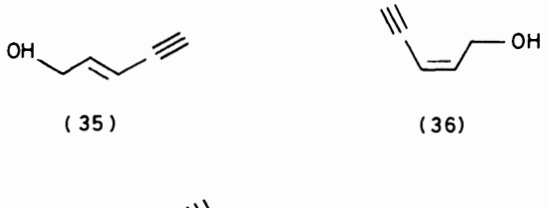
[a] Epoxidation was followed by acetylation and opening of the oxiran ring with acetate ion in acetic anhydride.

From (Z)-1-*Hydroxypenta*-2,4-*diene* (4).—In view of the successful synthetic approach to DL-arabinitol DL-(15) which it was possible to devise, starting from *trans*-3-hydroxypenta-2,4-diene (5), it was of interest to examine the stereochemical consequences for the analogous route emanating from the *cis*-isomer [5] (4) (Scheme 15). Compound (4) was obtained as the major component from the products which were formed in low yield when hydroxymethylvinylacetylene [35,36] (31) was hydrogenated in the presence of a Lindlar catalyst. It was isolated as its 3,5-dinitrobenzoate (32) by fractional crystallisation from aqueous methanol. Deacylation of (32) afforded pure (*Z*)-1-hydroxypenta-2,4-diene (4), which was treated with an anhydrous solution of t-butyl hydroperoxide and a catalytic quantity of vanadyl acetonylacetonate in toluene. Several reactions were attempted at different temperatures and for various different reaction times without any success. Fortunately, however, epoxidation of (4) was achieved at room temperature by *m*-chloroperbenzoic acid and the acetoxy-epoxypentene (33) was isolated after acetylation of the reaction

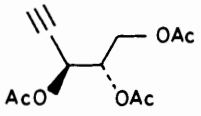


(4) (33) (34) (38)

Scheme 15. *Reagents:* i, *m*-$ClC_6H_4CO_3H$, $CHCl_3$; ii, Ac_2O, C_5H_5N; iii, Bu_4^nNOAc, Ac_2O; iv, NH_3, MeOH



(35) (36)



(37)

mixture. Treatment of (33) with tetra-n-butylammonium acetate afforded the triacetoxypentene (34) which was also obtained from (*Z*)-1-hydroxypent-2-en-4-yne (36) by a sequence of reactions involving: (*a*) epoxidation of (36) with performic acid, followed by (*b*) opening of the oxiran ring with potassium acetate to give (37), which was (*c*) hydrogenated in the presence of a Lindlar catalyst to yield compound (34). The trihydroxypentene (38) was isolated by distillation after deacetylation of (34). Compound (38) with the terminal C=C double bond was treated with t-butyl hydroperoxide in the presence of a range of catalytically active metal complexes, *e.g.* $Ti(OPr^i)_4$, $VO(acac)_2$, and $MoO_2(acac)_2$ in a variety of different solvents including benzene, toluene, dichloromethane, and 1,2-dichloroethane. Although the temperatures of the reaction mixtures were varied from room temperature to the reflux temperatures of the solvents, no reactions were detected. Also, when compound (38) was treated (*a*) with 2-hydroxyperoxyhexafluoropropanol prepared [34] *in situ* in ether, dichloromethane, 1,2-dichloroethane, or 1,1,2,2-tetrachloroethane at the reflux temperatures of the solvents, or (*b*) with peracids including *m*-chloroperbenzoic, *p*-nitroperbenzoic, and trifluoroperoxyacetic acids, no epoxidation occurred. Consequently, the acetoxyepoxypentene (33) was treated with trifluoroperacetic acid and the products of the crude reaction mixture were heated at 120 °C with tetra-n-butylammonium acetate and acetic anhydride. The result, which is summarised in Scheme 16, reveals very low overall stereoselectivity for xylitol penta-acetate (16) over DL-arabinitol penta-acetate DL-(15). However, we were encouraged by the observation that the terminal C=C double bond in the acetylated derivative (33) could at least be epoxidised. Thus, the triacetoxypentene (34) was treated with trifluoroperacetic acid under exactly the same conditions and only one of two possible diastereoisomeric epoxides was isolated (see Scheme 17). On treatment with tetra-n-butylammonium acetate in acetic anhydride, xylitol penta-acetate (16) and DL-arabinitol penta-acetate DL-(15) were characterised in the ratio 78 : 22 by g.l.c. and the former was isolated by fractional crystallisation. By analogy with the arguments presented previously for the transformation (27) ⟶ (28), the triacetoxyepoxypentane (39) is assumed to have the *xylo*-configuration as shown in Scheme 17. Since the epoxidation of (34) could only be carried out under conditions outlined in this Scheme, we do not consider a stereoselective synthesis of xylitol from (*Z*)-1-hydroxypenta-2,4-diene (4) to be competitive in a practical sense with that already described, starting from the much more readily available (*Z*)-(4*RS*)-4,5-epoxypent-2-enal (6).

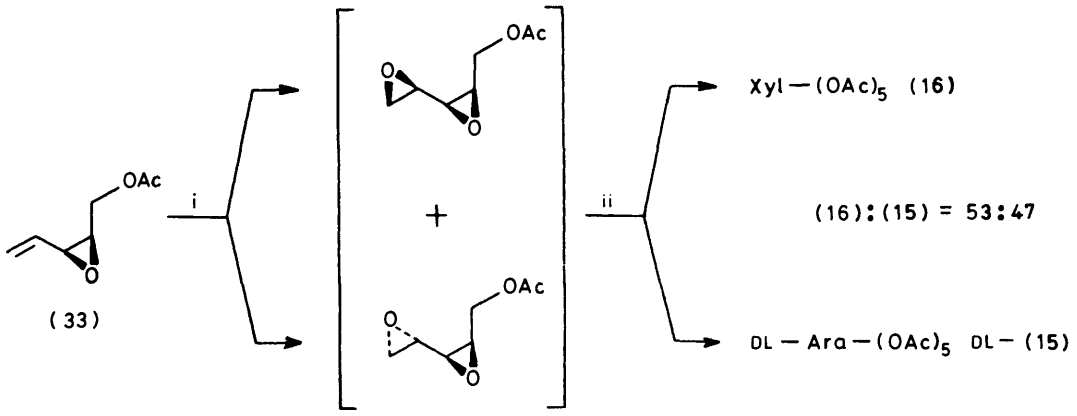
Conclusion

Since our own investigations were completed in 1981, several reports [37-40] have appeared in the literature describing stereocontrolled syntheses of (*a*) the tetritols, (*b*) the pentitols and some of the 2-deoxy- and 2-amino-2-deoxy-pentitols, (*c*) some of the hexitols, and (*d*) the 2,6-dideoxy-D-*arabino*- and 2,6-dideoxy-D-*ribo*-hexoses. The approaches are similar in concept and execution to those described in this paper, except that different achiral precursors [38-40] or chiral substrates [37,39,40] derived from 2,3-*O*-isopropylidene-D-glyceraldehyde by appropriate Wittig reactions have been employed. Highly regioselective epoxide ring openings were attained by implicating cyclic carbonates [37-40] (alditols) or cyclic urethanes [38,39] (aminodeoxyalditols) as intermediates or reductively cleaving [37,39-41] (deoxyalditols) the oxiran ring with Red-Al. For further chain extension, a benzenethiolate–Plummerer rearrangement–hydrolysis sequence [39] is also extremely efficient. In some of the reaction sequences, high stereoselectivities have also been achieved by resorting to the use of the excellent and elegant method of asymmetric epoxidation–kinetic resolution developed recently by Sharpless and his associates.[42] We chose to exclude, for both aesthetic and commercial reasons, the use of *chiral auxiliaries* from our attempts to synthesise stereoselectivity the *archiral pentitols*, xylitol (1) and ribitol (2). Similar aesthetically based objections can be raised against stereospecific synthetic routes [43] to xylitol (1) from D-glucose, irrespective of their potential commercial viability: the question of using a chiral natural product to prepare an achiral compound must always pose some doubts in the mind of a professional perfectionist!

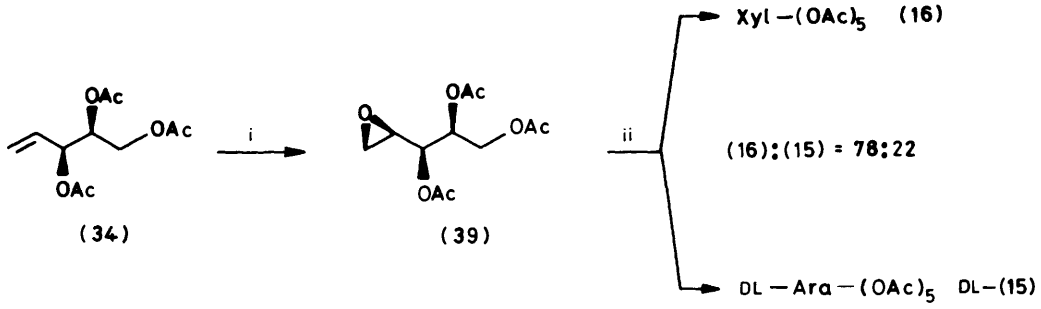
At present, xylitol (1) is obtained [1,44] commercially from xylan after a hydrolysis–hydrogenation sequence of reactions. It has about the same sweetness as sucrose but is *ca.* 15 times more expensive.[44] It has found application as a substitute for sucrose in the food industry and a large potential market was opening up for xylitol (1), particularly in the U.S.A. during the 1970's, on account of its non-cariogenic, or even anti-cariogenic, properties.[1] Alas, however, the commercial future for xylitol (1) in dietary supplements is at present bleak as a result of a privately commissioned report which suggests that, at high levels of consumption, it can cause cancer in mice, rats, and dogs.[45]

Experimental

The general methods have been described elsewhere.[7] Ether refers to diethyl ether.



Scheme 16. *Reagents:* i, CF_3CO_3H, Na_2HPO_4, CH_2Cl_2; ii, Bu^n_4NOAc, Ac_2O



Scheme 17. *Reagents:* i, CF_3CO_3H, Na_2HPO_4, CH_2Cl_2; ii, Bu^n_4NOAc, Ac_2O

(Z)-(4RS)-4,5-*Epoxypent*-2-*enal* [12-14] (6).—Photo-oxygenation of cyclopentadiene [15] (25 g, 0.38 mol) was carried out as described in the literature [13] to afford the title compound (6) (15.7 g, 0.16 mol, 42%), b.p. 37—42 °C at 0.15 mmHg (lit.,[12] b.p. 35 °C at 0.1 mmHg) [Found: *M* (mass spec.), 98; C, 61.0; H, 6.5%. Calc. for $C_5H_6O_2$: *M*, 98; C, 61.2; H, 6.1%]; δ ($CDCl_3$; 220 MHz) 10.12 (1 H, d, $J_{1,2}$ 5.4 Hz, CHO), 6.24 (1 H, t, $J_{2,3}$ 12.2 Hz, $J_{3,4}$ 12.2 Hz, 3-H), 6.20 (1 H, d × d, $J_{1,2}$ 5.4 Hz, $J_{2,3}$ 12.2 Hz, 2-H), 4.23 (1 H, m, 4-H), 3.16 (1 H, d × d, J_{gem} 6.1 Hz, $J_{4,5}$ 6.1 Hz, 5-H *cis* to 4-H), and 2.78 (1 H, d × d, J_{gem} 6.1 Hz, $J_{4,5}$ 2.9 Hz, 5-H *trans* to 4-H).

(2RS)-2-*Acetoxymethyl*-2,5-*dihydrofuran* (8).—The *cis*-epoxypentenal (6) (2.0 g, 20.4 mmol), dissolved in ethanol (10 ml), was added slowly with stirring to a solution of sodium borohydride (0.19 g, 5.1 mmol) in ethanol (10 ml) maintained at −40 °C. After 10 min, a solution of sodium hydroxide (0.2M) was added dropwise until the solution reached pH 10—11. This solution was allowed to warm up to room temperature before being concentrated to give a dark brown residue which was dissolved in ether, washed, and then dried (Na_2SO_4). Evaporation of the solvent yielded a pale yellow oil (0.69 g) which was treated immediately at room temperature for 2 h with a mixture of acetic anhydride (1.4 ml, 14.0 mmol) and pyridine (1.6 ml, 21.0 mmol) to afford a crude product which, on distillation, gave (2RS)-2-*acetoxymethyl*-2,5-*dihydrofuran* (8) (200 mg, 1.4 mmol, 7%), b.p. 90—100 °C at 2.0 mmHg [Found: (*M* − 60) (mass spec.), 82; C, 59.15; H, 7.0. $C_7H_{10}O_3$ requires *M*, 142; C, 59.2; H, 7.3%); δ ($CDCl_3$; 220 MHz) 6.00 (1 H, d × d, $J_{2,3}$ 2.0 Hz, $J_{3,4}$ 6.5 Hz, 3-H), 5.74 (1 H, m, 4-H), 5.00 (1 H, m, 2-H), 4.72—4.57 (2 H, m, 2 × 5-H), 4.16 and 4.05 (2 H, AB portion of an ABX system, J_{AB} 12.5 Hz, J_{AX} 3.5 Hz, J_{BX} 7.0 Hz, CH_2OAc), and 2.01 (3 H, s, OAc).

(Z)-(4RS)-1-*Acetoxy*-4,5-*epoxypent*-2-*ene* (10).—An ice-cold solution of sodium borohydride (5.0 g, 0.13 mol) in ethanol was added slowly with stirring to a solution of the *cis*-epoxypentenal (6) (50 g, 0.51 mol) in ethanol (180 ml), maintained at −40 °C. After 30 min, the solution was acidified with 0.5M-sulphuric acid (150 ml) to adjust the pH to 5—6. The reaction mixture was allowed to warm up to room temperature and the solvent was evaporated off. The residue was extracted with ether to give a colourless oil (53.6 g) which was dissolved immediately in THF (100 ml) and treated with a mixture of acetic anhydride (109 ml, 1.1 mol) and pyridine (127 ml, 1.6 mol) at 0 °C. The reaction was monitored by g.l.c. while the reaction mixture warmed up to room temperature. After 40 min, ether (1 l) was added and the ethereal solution was washed, dried (Na_2SO_4), and concentrated to yield a pale yellow oil which was distilled to afford (*Z*)-(4*RS*)-1-acetoxy-4,5-epoxypent-2-ene (10) (33.3 g, 0.23 mol, 45%), b.p. 80 °C at 0.2 mmHg (Found: C, 57.8; H, 7.1. Calc. for $C_7H_{10}O_3$: C, 59.2; H, 7.0%); δ ($CDCl_3$; 220 MHz) 5.80 (1 H, m, 2-H), 5.24 (1 H, t, $J_{2,3}$ 11.0 Hz, $J_{3,4}$ 8.5 Hz, 3-H), 4.74 (2 H, d, $J_{1,2}$ 8.5 Hz, 2 × 1-H), 3.65 (1 H, m, 4-H), 3.00 (1 H, d × d, J_{gem} 5.0 Hz, $J_{4,5}$ 3.5 Hz, 5-H *cis* to 4-H), 2.68 (1 H, d × d, J_{gem} 5.0 Hz, $J_{4,5}$ 2.5 Hz, 5-H *trans* to 4-H), and 2.02 (3 H, s, OAc).

(2RS)-2-*Acetoxymethyl*-2,5-*dihydrofuran* (8) *and* (Z)-(4RS)-1-*Acetoxy*-4,5-*epoxypent*-2-*ene* (10).—Sodium borohydride (50 mg, 1.3 mmol) in ethanol (5 ml) was added during a few minutes to a solution of the *cis*-epoxypentenal (6) (500 mg, 5.2 mmol) in ethanol (5 ml) maintained at −40 °C. The reaction mixture was left at −10 °C for 64 h. The solvent was then evaporated off, water was added to the residue, and the aqueous solution was extracted with ether to afford a clear liquid (400 mg). This product was acetylated and examined by g.l.c. on a 9-ft Silicone OV17 (3%) on Chromosorb WHP

column at 100 °C under a flow of nitrogen equivalent to 24 p.s.i.g. Two peaks, in the ratio 78 : 22, were identified. The faster and major component corresponded to (8) and the slower and minor component to (10).

(Z)-(4RS)-1,4,5-*Triacetoxypent*-2-*ene* (11).—The *cis*-epoxypenteneacetate (10) (15 g, 0.11 mol) was added to a solution of tetra-n-butylammonium acetate (2.1 g, 7.0 mmol) in acetic anhydride (84 ml) and the reaction mixture was heated at 105 °C for 18 h. Ether was added to the cooled reaction mixture and the ethereal solution was washed, dried (Na_2SO_4), and then treated with charcoal. After filtration and removal of the solvent under reduced pressure, a colourless oil remained. M.p.l.c. of this product on silica with ethyl acetate–light petroleum (b.p. 40—60 °C) (3 : 7) as eluant gave pure (Z)-(4RS)-1,4,5-*triacetoxypent*-2-*ene* (11) (18.5 g, 0.08 mol, 71%), b.p. 140 °C at 0.07 mmHg [Found: (M − 59) (mass spec.), 185; C, 54.2; H, 6.3. $C_{11}H_{16}O_6$ requires M, 244; C, 54.1; H, 6.6%]; δ ($CDCl_3$; 220 MHz) 5.77—5.70 (2 H, m, 2-H and 4-H), 5.50 (1 H, d × d × t, $J_{1,3}$ 1.0 Hz, $J_{2,3}$ 11.0 Hz, $J_{3,4}$ 9.0 Hz, 3-H), 4.77—4.64 (2 H, m, 2 × 1-H), 4.16 (1 H, d × d, J_{gem} 11.5 Hz, $J_{4,5}$ 3.5 Hz, 5-H), and 4.03 (1 H, d × d, J_{gem} 11.5 Hz, $J_{4,5}$ 6.5 Hz, 5-H).

(Z)-(4RS)-1,4,5-*Trihydroxypent*-2-*ene* (12).—The *cis*-triacetate (11) (16.7 g 0.07 mol) was added to a solution of ammonia (6%) in methanol (250 ml) and the reaction mixture was maintained at room temperature overnight. The ammoniacal methanol was removed under reduced pressure and the residual brown oil was redissolved in methanol, treated with charcoal, and then filtered. The solvent was evaporated off to give a pale yellow oil (12.6 g). Distillation of the oil afforded pure (*Z*)-(4*RS*)-1,4,5-trihydroxypent-2-ene (12) (7.5 g, 64 mmol, 94%), b.p. 195 °C at 0.01 mmHg [Found: (M − 31) (mass spec.), 87; C, 49.9; H, 8.8. Calc. for $C_5H_{10}O_3$: M, 118; C, 50.9; H, 8.5%], δ(CD_3OD; 400 MHz) 5.70 (1 H, d × d × d × d, $J_{1,2}$ 6.0, 7.0 Hz, $J_{2,3}$ 11.5 Hz, $J_{2,4}$ 1.5 Hz, 2-H), 5.45 (1 H, d × d × t, $J_{1,3}$ 1.5 Hz, $J_{2,3}$ 11.5 Hz, $J_{3,4}$ 8.5 Hz, 3-H), 4.14 (1 H, d × d × d × d, $J_{2,4}$ 1.5 Hz, $J_{3,4}$ 8.5 Hz, $J_{4,5}$ 5.2, 6.8 Hz, 4-H), 4.21 (1 H, d × d × d, J_{gem} 13.5 Hz, $J_{1,2}$ 7.0 Hz, $J_{1,3}$ 1.5 Hz, 1-H), 4.12 (1 H, d × d × d, J_{gem} 13.5 Hz, $J_{1,2}$ 6.0 Hz, $J_{1,3}$ 1.5 Hz, 1-H), 3.47 (1 H, d × d, J_{gem} 11.0 Hz, $J_{4,5}$ 6.8 Hz, 5-H), and 3.43 (1 H, d × d, J_{gem} 11.0 Hz, $J_{4,5}$ 5.2 Hz, 5-H).

rel-(2S,3R,4R)-1,2,5-*Triacetoxy*-3,4-*epoxypentane* (13) *and* rel-(2R,3R,4R)-1,2,5-*Triacetoxy*-3,4-*epoxypentane* (14).—The *cis*-trihydroxypentene (12) (6.0 g, 51.0 mmol) in THF (60 ml) was added to a solution of *p*-nitroperbenzoic acid (11.4 g, 61.2 mmol) in THF (60 ml). The reaction mixture was maintained at 0 °C for 2 h before being allowed to warm up to room temperature. After 1.5 h at this temperature, the solution was heated at 40 °C until the theoretical amount of *p*-nitroperbenzoic acid, as determined by iodometric titration, had been consumed. The solution was then cooled to room temperature and the precipitated *p*-nitrobenzoic acid was filtered off. A slurry of anhydrous potassium carbonate (24 g, 0.17 mol) in dry acetone (105 ml) was added to the filtrate and silica with ethyl acetate–light petroleum (b.p. 40—60 °C) (2 : 3) as eluant to give a mixture (4.16 g, 16.0 mmol, 31%) of the diastereoisomers (13) and (14). The isomers were separated by h.p.l.c. on silica with ethyl acetate–hexane (1 : 8) as eluant. The first component (isomer A) to elute from the column was characterised as *rel*-(2*S*,3*R*,4*R*)-1,2,5-triacetoxy-3,4-epoxypentane (13) (500 mg) (Found: C, 50.9; H, 6.9. Calc. for $C_{11}H_{16}O_7$: C, 50.8; H, 6.2%); δ ($CDCl_3$; 400 MHz) 4.85 (1 H, d × d × d, $J_{2,3}$ 8.1 Hz, $J_{1,2}$ 5.7, 3.2 Hz, 2-H), 4.48 (1 H, d × d, J_{gem} 12.6 Hz, $J_{4,5}$ 3.9 Hz, 5-H), 4.45 (1 H, d × d, J_{gem} 12.1 Hz, $J_{1,2}$ 3.2 Hz, 1-H), 4.26 (1 H, d × d, J_{gem} 12.1 Hz, $J_{1,2}$ 5.7 Hz, 1-H), 4.11 (1 H, d × d, J_{gem} 12.6 Hz, $J_{4,5}$ 7.1 Hz, 5-H), 3.28 (1 H, d × d × d, $J_{4,5}$ 3.9, 7.1 Hz, $J_{3,4}$ 4.2 Hz, 4-H), 3.15 (1 H, d × d, $J_{3,4}$ 4.2 Hz, $J_{2,3}$ 8.1 Hz, 3-H), and 2.10 (9 H, s, 3 × OAc). The second component (isomer B) to elute from the column was characterised as *rel*-(2*R*,3*R*,4*R*)-1,2,5-triacetoxy-3,4-epoxypentane (14) (650 mg) (Found: C, 50.8; H, 6.4. Calc. for $C_{11}H_{16}O_7$: C, 50.8; H, 6.15%); δ ($CDCl_3$; 400 MHz) 5.00 (1 H, d × d × d, $J_{3,4}$ 8.3 Hz, $J_{1,2}$ 4.6, 5.6 Hz, 2-H), 4.40 (1 H, d × d, J_{gem} 12.2 Hz, $J_{4,5}$ 4.2 Hz, 5-H), 4.33 (1 H, d × d, J_{gem} 12.0 Hz, $J_{1,2}$ 4.6 Hz, 1-H), 4.18 (1 H, d × d, J_{gem} 12.2 Hz, $J_{4,5}$ 6.8 Hz, 5-H), 4.16 (1 H, d × d, J_{gem} 12.0 Hz, $J_{1,2}$ 5.6 Hz, 1-H), 3.33 (1 H, d × d × d, $J_{4,5}$ 4.2, 6.8 Hz, $J_{3,4}$ 4.4 Hz, 4-H), 3.24 (1 H, d × d, $J_{3,4}$ 4.4 Hz, $J_{2,3}$ 8.3 Hz, 3-H), and 2.13, 2.12, and 2.10 (9 H, 3 × s, 3 × OAc).

Reactions of rel-(2S,3R,4R)-1,2,5-*Triacetoxy*-3,4-*epoxypentane* (13).—(*a*) *With tetra-n-butylammonium acetate in acetic anhydride.* Isomer A (13) (9.0 mg) was treated with tetra-n-butylammonium acetate (0.8 mg) in acetic anhydride (0.2 ml) at 121 °C and the reaction was followed by g.l.c. (180 °C). The results are summarised in Figures 3—5. Initially, DL-arabinitol penta-acetate DL-(15) was the major product of the reaction. However, after *ca.* 2 h, xylitol penta-acetate (16) became the major product and eventually after 23 h, when the reaction was complete, the ratio of DL-(15) to (16) was 35 : 65. Also, the peak on the g.l.c. trace corresponding to the starting material showed an unexpected and dramatic increase in its relative intensity (see Figure 3) before undergoing the expected decrease. This behaviour is consistent with the production of an intermediate [compound (Z)] during the reaction of isomer A (13) to afford both DL-(15) and (16).

(*b*) *With acetic anhydride.* Isomer A (13) (13.4 mg, 0.051 mmol) was heated at 121 °C in acetic anhydride (1.0 ml) and the reaction was followed by g.l.c. (180 °C). The reaction was complete after 34 h when the ratio of DL-arabinitol penta-acetate DL-(15) to xylitol penta-acetate (16) was 36 : 64 and the isolated yield of these penta-acetates (0.44 mmol) was 86%. The reaction follows a course similar to that described for the reaction involving added acetate ion in method (*a*) above.

Reactions of rel-(2R,3R,4R)-1,2,5-*Triacetoxy*-3,4-*epoxypentane* (14).—(*a*) *With tetra-n-butylammonium acetate in acetic anhydride.* Isomer B (14) (8.4 mg) was treated with tetra-n-butylammonium acetate (0.5 mg) in acetic anhydride (0.17 ml) at 120 °C and the reaction was followed (see Figure 4) by g.l.c. The reaction was complete after 23.5 h and there

Xylitol (1).—A mixture of isomers A (13) and B (14), obtained on epoxidation of the triol (12) with *p*-nitroperbenzoic acid in chloroform, was heated with tetra-n-butylammonium acetate in acetic anhydride at 112 °C for 16 h. G.l.c. analysis indicated that the ratio of DL-arabinitol penta-acetate DL-(15) : xylitol penta-acetate (16) was 24 : 76. This mixture of penta-acetates was subjected to chromatography on silica using ethyl acetate–light petroleum (b.p. 60—80 °C) (3 : 7) as eluant to afford xylitol penta-acetate (16) in 21% isolated yield. This product was allowed to stand at room temperature in 10% methanolic hydrogen chloride in 16 h. Evaporation of the solvent gave an oil which crystallised from methanol as pure xylitol (1), m.p. 85—90 °C (lit.,[46] m.p. 93—94.5 °C) (27% isolated yield). Acetylation of this compound afforded xylitol penta-acetate (16) as the sole product.

rel-(1s,3R,4r,5S)-3,5-*Bisacetoxymethyl*-1-*methyl*-2,6,7-*trioxabicyclo*[2.2.1]*heptane* (23).—Isomer A (13) (225 mg, 0.87 mmol) and tetra-n-butylammonium acetate (12.3 mg, 0.04 mmol) were added to a solution of hexadecane (0.014 mol, g.l.c. internal standard) in acetic anhydride (4.1 ml). The reaction mixture was heated to 112 °C and samples were analysed by g.l.c. (180 °C) at intervals of 1 h. After 5 h, the ratio of compound (Z) : isomer A (13) had reached its maximum and the reaction mixture was allowed to cool down to room temperature. Excess of acetic anhydride was removed under high vacuum. Immediately, a solvent mixture of ethyl acetate–light petroleum (b.p. 60—80 °C) (3 : 7) (*ca.* 5 ml) was added to the pale yellow residual oil. After a few minutes, a white solid crystallised out from this solution on standing at room temperature. The crystals were filtered off, washed with a small amount of solvent, and dried under high vacuum. They were unstable and had to be stored in the presence of solid CO_2. They were characterised as rel-(1s,3R,4r,5S)-3,5-*bisacetoxymethyl*-1-*methyl*-2,6,7-*trioxabicyclo*[2.2.1]*heptane* (23) (68 mg, 0.26 mmol, 30%), m.p. 112—114 °C (Found: C, 51.1; H, 6.5. $C_{11}H_{16}O_7$ requires C, 50.8; H, 6.2%), δ ($CDCl_3$; 400 MHz) 4.71 (1 H, s, 4-H), 4.06 (2 H, A portion of an AB_2 system, J_{AB} 6.5 Hz, $J_{3,4} = J_{4,5} < 0.2$ Hz, 3-H and 5-H), 4.03 (4 H, B portion of an AB_2 system, J_{AB} 6.5 Hz, 2 × CH_2-OAc), 2.10 (6 H, s, 2 × OAc), and 1.78 (3 H, s, Me). G.l.c. analysis of the crystals revealed that they have the same retention time as isomer A (13) and so (23) corresponds to compound (Z).

(E)-(4RS)-4,5-*Epoxypent*-2-*enal* [12,13] (7).—The *cis*-epoxypentenal (6) (30.0 g) was added to a solution of triphenylphosphine (4.2 g) in dry benzene (200 ml) and the reaction mixture was allowed to stand at room temperature for 16 h. The solvent was removed under vacuum and the residual oil was distilled under nitrogen at reduced pressure to afford a colourless oil which was shown to be (*E*)-(4*RS*)-4,5-epoxypent-2-enal (7) (25.9 g, 86%), b.p. 46.5 °C at 0.25 mmHg (lit.,[12] b.p. 36 °C at 0.1 mmHg) (Found: C, 60.5; H, 6.8. Calc. for $C_5H_6O_2$: C, 60.6; H, 6.8%), δ ($CDCl_3$; 100 MHz) (*cf.* refs. 12 and 13) 9.60—9.54 (1 H, m, CHO), 6.54—6.40 (2 H, m, 2-H and 3-H), 3.68—3.50 (1 H, m, 4-H), 3.16 (1 H, d × d, J_{gem} 5.7 Hz, $J_{4,5}$ 4.3 Hz, 5-H *cis* to 4-H), and 2.80 (1 H, d × d, J_{gem} 5.7 Hz, $J_{4,5}$ 2.8 Hz, 5-H *trans* to 4-H).

(E)-(4RS)-1-*Acetoxy*-4,5-*epoxypent*-2-*ene* (21) *and* (E)-(4RS)-1,4,5-*Triacetoxypent*-2-*ene* (22).—An ice-cold solution of sodium borohydride (2.65 g, 0.07 mol) in ethanol (230 ml) was added slowly with stirring to a solution of the *trans*-epoxypentenal (7) (26.0 g, 0.27 mol) in ethanol (230 ml), maintained at −30 °C. When the addition of the borohydride solution was complete, the reaction mixture was stirred for a further 5 min. Dilute sulphuric acid (0.5M; *ca.* 5 ml) was added slowly to the reaction mixture with stirring until the solution acquired a pH of *ca.* 6. This solution was concentrated under reduced pressure and the residue was extracted with ether (500—600 ml) and dried (Na_2SO_4). The solvent was evaporated off to afford a pale yellow oil (25.6 g) which was dissolved immediately in THF (50 ml) and treated with a mixture of acetic anhydride (52.5 ml, 0.5 mol) and pyridine (61 ml, 0.8 mol) at 0 °C. The acetylation was monitored by g.l.c. (150 °C); it transpired that prolonged reaction times gave lower yields. After *ca.* 45 min, ether (500 ml) was added to the reaction mixture and the ethereal solution was washed and then dried (Na_2SO_4). The solvent was evaporated off under reduced pressure to give a pale yellow oil (21.8 g) which was purified by m.p.l.c. on silica with ethyl acetate–light petroleum (b.p. 40—60 °C) (1 : 4) as eluant. The first component to be eluted from the column was characterised as (*E*)-(4*RS*)-1-acetoxy-4,5-epoxypent-2-ene (21) (7.7 g, 0.05 mol, 20%), b.p. 109 °C at 0.05 mmHg (Found: C, 58.3; H, 7.1. Calc. for $C_7H_{10}O_3$: C, 59.2; H, 7.0%); δ ($CDCl_3$; 100 MHz) 6.04 (1 H, d × t, $J_{1,2}$ 5.7 Hz, $J_{2,3}$ 15.7 Hz, 2-H), 5.48 (1 H, d × d × t, $J_{1,3}$ 1.4 Hz, $J_{2,3}$ 15.7 Hz, $J_{3,4}$ 7.9 Hz, 3-H), 4.58 (2 H, d × d, $J_{1,2}$ 5.7 Hz, $J_{1,3}$ 1.4 Hz, 2 × 1-H), 3.45—3.29 (1 H, m, 4-H), 3.00 (1 H, d × d, J_{gem} 5.7 Hz, $J_{4,5}$ 4.3 Hz, 5-H *cis* to 4-H), 2.68 (1 H, d × d, J_{gem} 5.7 Hz, $J_{4,5}$ 2.9 Hz, 5-H *trans* to 4-H), and 2.10 (3 H, s, OAc). The second component which was eluted from the column was characterised as (E)-(4RS)-1,4,5-*triacetoxypent*-2-*ene* (22) (4.33 g, 0.02 mol, 6.7%) (Found: C, 54.3; H, 6.6. $C_{11}H_{16}O_6$ requires C, 54.1; H, 6.6%); δ ($CDCl_3$; 400 MHz) 5.92 (1 H, d × t × d, $J_{1,2}$ 5.8 Hz, $J_{2,3}$ 14.0 Hz, $J_{2,4}$ 1.2 Hz, 2-H), 5.74 (1 H, d × d × t, $J_{1,3}$ 1.3 Hz, $J_{2,3}$ 14.0 Hz, $J_{3,4}$ 4.9 Hz, 3-H), 5.55—5.51 (1 H, m, 4-H), 4.58 (2 H, d, $J_{1,2}$ 5.8 Hz, 2 × 1-H), 4.25 (1 H, d × d, J_{gem} 11.9 Hz, $J_{4,5}$ 3.7 Hz, 5-H), 4.10 (1 H, d × d, J_{gem} 11.9 Hz, $J_{4,5}$ 7.0 Hz, 5-H), and 2.10, 2.08, and 2.07 (9 H, 3 × s, 3 × OAc).

(E)-(4RS)-1,4,5-*Trihydroxypent*-2-*ene* (25).—The *trans*-triacetate (22) (3.1 g, 13 mmol) was added to a solution (50 ml) of 6% ammonia in methanol and the reaction mixture was allowed to stand at room temperature overnight. The solution was concentrated under reduced pressure and the residual oil was dissolved in methanol and refluxed in the presence of charcoal for 5 min. After filtration, the solvent was evaporated off and the oil distilled at 0.05 mmHg. Following sublimation of a white solid between 80 and 100 °C, a viscous yellow distillate was obtained at higher temperatures and was shown to be (*E*)-(4*RS*)-1,4,5-trihydroxypent-2-ene (25) (1.3 g, 10.9 mmol, 84%), b.p. 160 °C at 0.05 mmHg (Found: C, 49.3; H, 9.0. Calc. for $C_5H_{10}O_3$: C, 50.9; H, 8.5%); δ (CD_3OD; 400 MHz) 5.87 (1 H, d × t × d, $J_{1,2}$ 5.0 Hz, $J_{2,3}$ 15.5 Hz, $J_{2,4}$ 1.2 Hz, 2-H), 5.71 (1 H, d × d × t, $J_{1,3}$ 1.2 Hz, $J_{2,3}$ 15.5 Hz, $J_{3,4}$ 6.0 Hz, 3-H), 4.14—4.11 (1 H, m, $J_{1,4}$ 1.2 Hz, $J_{2,4}$ 1.2 Hz, $J_{3,4}$ 6.0 Hz, $J_{4,5}$ 4.8, 6.8 Hz), 4.08 (2 H, d × d × d, $J_{1,2}$ 5.0 Hz, $J_{1,3}$ 1.2 Hz, $J_{1,4}$ 1.2 Hz, 2 × 1-H), 3.50 (1 H, d × d, J_{gem} 11.0 Hz, $J_{4,5}$ 4.8 Hz, 5-H), and 3.45 (1 H, d × d, J_{gem} 11.0 Hz, $J_{4,5}$ 6.8 Hz, 5-H).

Quantitative Experiments on the Catalytic Hydroxylations of the cis-*Olefins* (10), (11), *and* (12) *and the* trans-*Olefins* (21), (22), and (25).—t-Butyl hydroperoxide, free from di-t-butyl peroxide and obtained from Aldrich, was used without purification in hydroxylations catalysed by osmium tetraoxide. A stock catalyst solution was prepared [22] from osmium tetraoxide (100 mg) and t-butyl hydroperoxide (0.13 ml) in t-butyl alcohol (20 ml) and was stored at −15 °C until it was required. Small samples (*ca.* 20 mg) of the *cis*-olefins (10), (11), and (12) and the *trans*-olefins (21), (22), and (25) were treated in turn with the catalytic hydroxylating reagent and an aqueous solution of t-butyl hydroperoxide. The reaction mixtures were

stirred at room temperature and the reactions were monitored after acetylation (acetic anhydride and pyridine) by g.l.c. (180 °C). The percentage ratios of the penta-acetates DL-(15), (16), and (17), present after complete conversions of the olefins into products, are recorded in Table 2.

Ribitol (2).—A small quantity (0.2 ml) of the stock solution of the hydroxylation catalyst was added to a solution of the *cis*-triacetate (11) (0.5 g, 2.0 mmol), tetraethylammonium acetate tetrahydrate (0.13 g, 0.51 mmol), and t-butyl hydroperoxide (0.48 ml, 3.62 mmol) in acetone (5 ml). The reaction mixture was maintained at 50 °C overnight and then it was heated at 60 °C until g.l.c. (180 °C) analysis indicated that all the substrate had been consumed. After cooling, the reaction mixture was treated with acetic anhydride (1.7 ml) in pyridine (2.0 ml) and left to stand at room temperature overnight. Ether was added and the ethereal solution was washed and then dried (Na_2SO_4). The solvent was evaporated off to give an oil (0.66 g) which was purified by m.p.l.c. on silica with ethyl acetate–light petroleum (b.p. 40—60 °C) as eluant. The major product was treated with 9% methanolic hydrogen chloride and allowed to stand overnight at room temperature. The solvent was removed to give a pale yellow oil which was crystallised from methanol at −15 °C to afford ribitol (2) (47.6 mg, 0.13 mmol, 6.2%), m.p. 98—102 °C (lit.,[46] m.p. 102 °C) (Found: C, 39.5; H, 7.6. Calc. for $C_5H_{12}O_5$: C, 39.6; H, 7.9%). Acetylation of this compound yielded ribitol penta-acetate (17) as the sole product.

(E)-1-*Hydroxypenta*-2,4-*diene*[6,47,48] (5).—Reduction of vinylacrylic acid, m.p. 70—71 °C (lit.,[48] m.p. 72 °C) (72 g, 0.74 mol) was carried out as described in the literature to afford the title compound (5) (10 g, 20%), b.p. 46—47.5 °C at 7 mmHg (lit.,[6] b.p. 66—68 °C at 26 mmHg) [Found: *M* (mass spec.), 84. C_5H_8O requires *M*, 84]; δ ($CDCl_3$; 220 MHz) 6.49—6.15 (2 H, m, 3-H and 4-H), 5.85 (1 H, m, 2-H), 5.22 (1 H, d, $J_{4,5}$ 17.5 Hz, 5-H *trans* to 4-H), 5.10 (1 H, d, $J_{4,5}$ 10.0 Hz, 5-H *cis* to 4-H), 4.12 (2 H, d, $J_{1,2}$ 6.0 Hz, 1-H), and 2.69 (1 H, bs, OH).

rel-(3R,4S)-5-*Acetoxy*-3,4-*epoxypent*-1-*ene* (26).—A 63% aqueous solution of t-butyl hydroperoxide (48.6 g, 0.34 mol) was added dropwise during 2 h to a solution of the *trans*-pentadienol (5) (12.6 g, 0.15 mol) and vanadyl acetonylacetonate (400 mg, 1.5 mmol) in toluene (760 ml). The reaction mixture was stirred under nitrogen at room temperature. The reaction was monitored by iodiometric titration. The theoretical consumption of the hydroperoxide was attained after *ca.* 5 h and the reaction mixture was treated with acetic anhydride (59 g, 0.75 mol) in pyridine (53 g, 1.5 mol) and allowed to stand at room temperature for 6 h. This solution was poured on to crushed ice and the organic layer was separated, washed, and then dried (Na_2SO_4). Evaporation of the solvent gave a dark brown oil (22 g) which was purified by fractional distillation under nitrogen at reduced pressure to give *rel*-(3*R*,4*S*)-5-acetoxy-3,4-epoxypent-1-ene (26) (7.1 g, 33%), b.p. 46—50 °C at 1.5 mmHg [Found: (*M* − 60) (mass spec.), 82; C, 59.2; H, 7.0. Calc. for $C_7H_{10}O_3$: *M*, 142; C, 58.0; H, 7.0%]; δ ($CDCl_3$; 220 MHz) 5.63—5.52 (2 H, m, 2 × 1-H), 5.38—5.30 (1 H, m, 2-H), 4.40 (1 H, d × d, J_{gem} 12.3 Hz, $J_{4,5}$ 2.9 Hz, 5-H), 3.98 (1 H, d × d, J_{gem} 12.3 Hz, $J_{4,5}$ 6.1 Hz, 5-H), 3.32—3.24 (1 H, m, 3-H), 3.16—3.08 (1 H, m, 4-H), and 2.10 (3 H, s, OAc).

rel-(3R,4R)-3,4,5-*Triacetoxypent*-1-*ene* (27).—The acetoxy-epoxypentene (26) (7.1 g, 50 mmol) was added to a solution of tetra-n-butylammonium acetate (1.8 g, 5.0 mmol) in acetic anhydride (5.1 g) and the reaction mixture was maintained at 90 °C overnight. On cooling down to room temperature, ether was added and the ethereal solution was washed, dried (Na_2SO_4), and treated with charcoal. The solid was filtered off and the filtrate was concentrated to give an oil (7.1 g) which was purified by distillation under nitrogen at reduced pressure (0.3 mmHg) to afford rel-(3R,4R)-3,4,5-*triacetoxypent*-1-*ene* (27) (3.3 g, 27%) [Found: (*M* − 59) (mass spec.), 185; C, 53.9; H, 6.8. $C_{11}H_{16}O_6$ requires *M*, 244; C, 54.1; H, 6.6%]; δ ($CDCl_3$; 400 MHz) 5.80 (1 H, d × d × d, $J_{1,2}$ 17.2, 10.5 Hz, $J_{2,3}$ 6.7 Hz, 2-H), 5.48 (1 H, d × d × t, $J_{1,3}$ 1.2 Hz, $J_{2,3}$ 6.7 Hz, $J_{3,4}$ 4.1 Hz, 3-H), 5.37 (1 H, d × t, J_{gem} 1.3 Hz, $J_{1,3}$ 1.2 Hz, $J_{1,2}$ 17.2 Hz, 1-H *trans* to 2-H), 5.33 (1 H, d × t, J_{gem} 1.3 Hz, $J_{1,3}$ 1.2 Hz, $J_{1,2}$ 10.5 Hz, 1-H *cis* to 2-H), 5.23 (1 H, d × d × d, $J_{3,4}$ 4.1 Hz, $J_{4,5}$ 7.2, 3.5 Hz, 4-H), 4.26 (1 H, d × d, J_{gem} 12.2 Hz, $J_{4,5}$ 3.5 Hz, 5-H), 4.17 (1 H, d × d, J_{gem} 12.2 Hz, $J_{4,5}$ 7.2 Hz, 5-H), and 2.09, 2.08, and 2.06 (9 H, 3 × s, 3 × OAc).

rel-(2R,3S,4R)-1,2,3-*Triacetoxy*-4,5-*epoxypentane* (28).—A solution of peroxytrifluoroacetic acid (4.2 mmol) in dichloromethane (10 ml) was added in portions to a refluxing stirred suspension of the triacetoxypentene (27) (0.81 g, 3.32 mmol) and freshly dried powdered disodium hydrogen phosphate (2.13 g, 15.0 mmol) in dichloromethane (10 ml). The reaction was monitored by g.l.c. (200 °C), which also indicated the presence of only *one* major product. After 3 h, the reaction mixture was cooled down to room temperature and the solid was filtered off. The filtrate was washed, dried (Na_2SO_4), and concentrated to give a colourless oil (0.5 g) which was purified by preparative g.l.c. on a Silicone OV17 (2%) column at 180 °C to afford *rel*-(2*R*,3*S*,4*R*)-1,2,3-triacetoxy-4,5-epoxypentane (28) (51.8 mg, 0.2 mmol, 6%) (Found: C, 49.6; H, 6.3. Calc. for $C_{11}H_{16}O_7$: C, 50.8; H, 6.2%); δ ($CDCl_3$; 220 MHz) 5.36—5.27 (1 H, m, 2-H), 4.95 (1 H, d × d, $J_{2,3}$ 5.5 Hz, $J_{3,4}$ 4.5 Hz, 3-H), 4.35 (1 H, d × d, J_{gem} 12.0 Hz, $J_{1,2}$ 3.0 Hz, 1-H), 4.20 (1 H, d × d, J_{gem} 12.0 Hz, $J_{1,2}$ 6.0 Hz, 1-H), 3.20—3.13 (1 H, m, 4-H), 2.83 (1 H, d × d, J_{gem} 5.0 Hz, $J_{4,5}$ 4.0 Hz, 5-H *cis* to 4-H), 2.64 (1 H, d × d, J_{gem} 5.0 Hz, $J_{4,5}$ 2.5 Hz, 5-H *trans* to 4-H), and 2.75, 2.06, and 2.03 (9 H, 3 × s, 3 × OAc).

DL-*Arabinitol Penta-acetate* DL-(15).—*Method A.* The triacetoxyepoxypentane (28) (113 mg, 0.44 mmol) was added to a solution (5 ml) of 6% ammonia in methanol and the reaction mixture was allowed to stand (45 min) at room temperature until g.l.c. analysis indicated that the reaction was complete. The solution was concentrated under reduced pressure and the residual oil (77 mg) was dissolved in 1% sulphuric acid (5 ml). After refluxing this solution for 60 min, Amberlite IR 45 (OH) was added to neutralise it. The filtrate obtained after filtration was concentrated to a yellow oil (42 mg) which was acetylated with acetic anhydride (0.14 g, 1.4 mmol) in pyridine (0.22 g, 2.8 mmol) at 60 °C for 60 min to give a product (36 mg) in the form of a colourless oil after work-up, which crystallised on standing. Recrystallisation from methanol afforded pure DL-arabinitol penta-acetate DL-(15) (16 mg), m.p. 93—96 °C (lit.,[46] m.p. 96—96.5 °C) (Found: C, 49.5; H, 6.1. Calc. for $C_{15}H_{22}O_{11}$: C, 49.7, H, 6.1%); δ (^{13}C) ($CDCl_3$) 170.2, 170.0, 169.7, 169.4, and 169.3 (CO), 68.2 and 67.9 (CH), 61.9 and 61.6 (CH_2), and 20.6 p.p.m. (CO*Me*).

Method B. G.l.c. indicated that when the triacetoxyepoxypentane (28) was treated with tetra-n-butylammonium acetate in acetic anhydride at 120 °C, conversion into DL-arabinitol penta-acetate DL-(15) with 91% stereoselectivity was complete within 24 h. The minor product which was obtained was characterised as ribitol penta-acetate (17) by g.l.c.

Method C. A small quantity (0.2 ml) of the stock solution of the hydroxylation catalyst was added to a solution of the

trans-triacetoxypentene (22) (500 mg, 2.0 mmol), tetraethylammonium acetate tetrahydrate (130 mg, 0.51 mmol), and t-butyl hydroperoxide (0.48 ml, 3.62 mmol) in acetone. This reaction mixture was maintained at 50 °C overnight and then heated to 60 °C until g.l.c. (180 °C) analysis indicated that all the substrate had been consumed. After cooling, the reaction mixture was treated with acetic anhydride (1.7 ml) in pyridine (2.0 ml) and allowed to stand at room temperature overnight. Ether was added and the ethereal solution was washed and then dried (Na_2SO_4). The dry ethereal solution was concentrated to give an oily liquid together with a white crystalline solid. This heterogeneous mixture was dissolved in the minimum quantity of dry methanol and then cooled to −15 °C. The crystals were filtered off and shown to be DL-arabinitol penta-acetate DL-(15) (220 mg, 0.61 mmol, 31%), m.p. 94—96 °C (lit.,[46] m.p. 96—96.5 °C).

5-Hydroxypent-2-en-4-yne [35,36] (31).—Coupling of propargyl alcohol with vinyl bromide was carried out as described in the literature [35] to afford the title compound (31) (23%), b.p. 64—66 °C at 10 mmHg (lit.,[36] b.p. 58 °C at 12 mmHg); δ ($CDCl_3$; 220 MHz) 5.80 (d × d × t, $J_{1,4}$ 1.0 Hz, $J_{4,5}$ 10.0, 16.0 Hz, 4-H), 5.65 (1 H, d × d, J_{gem} 2.0 Hz, $J_{4,5}$ 16.0 Hz, 5-H *trans* to 4-H), 5.50 (1 H, d × d, J_{gem} 2.0 Hz, $J_{4,5}$ 10.0 Hz, 5-H *cis* to 4-H), 4.36 (2 H, d, $J_{1,4}$ 1.0 Hz, 2 × 1-H), and 3.20 (1 H, s, OH).

(Z)-1-(3,5-*Dinitrobenzoyloxy*)*penta*-2,4-*diene* (32).—A freshly prepared and dry catalyst consisting of palladium (5%) on barium sulphate (5.0 g) was added as a slurry in dry pyridine to a solution of the pentenynol (31) (19 g, 0.23 mol) in dry pyridine (75 ml). This suspension was stirred in the absence of light under hydrogen until the theoretical volume (5.5 l) had been consumed. The dark brown reaction mixture was filtered and concentrated under reduced pressure. The residue was distilled under vacuum through a column packed with glass helices. The major fraction (3.4 g) from this distillation, b.p. 60—61.5 °C at 20 mmHg, was dissolved in benzene (*ca.* 5 ml) and treated with a solution of 3,5-dinitrobenzoyl chloride (10.0 g, 40.5 mmol) in pyridine (5 ml), and the reaction mixture was stirred at room temperature for 15 min. The solid was filtered off and the filtrate washed, dried (Na_2SO_4), and concentrated to afford a residue which was recrystallised from methanol–water to give pale yellow crystals of (Z)-1-(3,5-*dinitrobenzoyloxy*)*penta*-2,4-*diene* (32) (6.4 g, 10%), m.p. 62—66 °C (Found: C, 51.5; H, 3.6; N, 10.1. $C_{12}H_{10}N_2O_6$ requires C, 51.8; H, 3.6; N, 10.1%); δ ($CDCl_3$; 220 MHz) 9.14 and 9.07 (3 H, AB_2 system, J_{AB} 1.0 Hz, aromatic H), 6.70 (1 H, d × t, $J_{3,4}$ 10 Hz, $J_{4,5}$ 9.0, 16.0 Hz, 4-H), 6.27 (1 H, t, $J_{2,3}$ 10.0 Hz, $J_{3,4}$ 10.0 Hz, 3-H), 5.59 (1 H, m, 2-H), 5.41 and 5.26 (2 H, d × d × d, J_{gem} 1.0 Hz, $J_{4,5}$ 9.0, 16.0 Hz, 2 × 5-H), and 5.07 (2 H, d, $J_{1,2}$ 7.0 Hz, 2 × 1-H).

(Z)-1-*Hydroxypenta*-2,4-*diene* [5] (4).—The 3,5-dinitrobenzoate (32) (6.4 g, 23 mmol) was added to 6% ammoniacal methanol (100 ml) and the reaction mixture was stirred for a few minutes at room temperature. The precipitated methyl 3,5-dinitrobenzoate was filtered off and the filtrate was concentrated under reduced pressure to afford an oily residue. This was distilled to yield a colourless oil which was characterised as (*Z*)-1-hydroxypenta-2,4-diene (4) (1.3 g, 15.5 mmol, 67%), b.p. 58 °C at 13 mmHg (lit.,[5] b.p. 79—80 °C at 35 mmHg); δ ($CDCl_3$; 220 MHz) 6.54 (1 H, d × t, $J_{3,4}$ 11.0 Hz, $J_{4,5}$ 10.0, 18.0 Hz, 4-H), 6.02 (1 H, t, $J_{2,3}$ 10.0 Hz, $J_{3,4}$ 11.0 Hz, 3-H *cis* to 2-H), 5.54 (1 H, m, 2-H), 5.27 and 5.07 (2 H, d × d × d, J_{gem} 1.0 Hz, $J_{4,5}$ 10.0, 18.0 Hz, 2 × 5-H), 4.25 (2 H, d, $J_{1,2}$ 6.5 Hz, 2 × 1-H), and 3.52 (1 H, s, OH).

rel-(3R,4S)-5-*Acetoxy*-3,4-*epoxypent*-1-*ene* (33).—The *cis*-pentadienol (4) (1.0 g, 12.0 mmol) was added to a solution of *m*-chloroperbenzoic acid (3.0 g, 14.4 mmol) in chloroform (144 ml). This solution was stirred at room temperature and the reaction was monitored by g.l.c. (100 °C). After 6 h, the excess of *m*-chloroperbenzoic acid was destroyed by addition of sodium metabisulphite. The suspension was filtered and the filtrate was stirred vigorously with calcium hydroxide [49] until the solution was neutral. The solid was filtered off and the filtrate was dried (Na_2SO_4). This solution was treated with acetic anhydride (6 ml, 60 mmol) and pyridine (9 ml, 120 mmol) at room temperature overnight. This reaction was washed and then dried (Na_2SO_4). The solvent was removed under reduced pressure to give a pale yellow oil (1.9 g) which was distilled to afford *rel*-(3*R*,4*S*)-5-acetoxy-3,4-epoxypent-1-ene (33) (1.06 g, 7.5 mmol, 62%), b.p. 90—95 °C at 5 mmHg (Found: C, 58.6; H, 7.8. Calc. for $C_7H_{10}O_3$: C, 59.1; H, 7.0%); δ ($CDCl_3$; 220 MHz) 5.75—5.59 (1 H, m, 2-H), 5.45 (1 H, d × d, J_{gem} 1.5 Hz, $J_{1,2}$ 16.5 Hz, 1-H *trans* to 2-H), 5.34 (1 H, d × d, J_{gem} 1.5 Hz, $J_{1,2}$ 10.0 Hz, 1-H *cis* to 2-H), 4.22 (1 H, d × d, J_{gem} 12.5 Hz, $J_{4,5}$ 4.0 Hz, 5-H), 4.00 (1 H, d × d, J_{gem} 12.5 Hz, $J_{4,5}$ 7.0 Hz, 5-H), 3.50 (1 H, d × d, $J_{2,3}$ 6.0 Hz, $J_{3,4}$ 5.5 Hz, 3-H), and 2.11 (3 H, s, OAc).

(E)-1-*Hydroxypent*-2-*en*-4-*yne* (35) *and* (Z)-1-*Hydroxypent*-2-*en*-4-*yne* (36).—A solution of sodamide in liquid ammonia was obtained from sodium (27.6 g) and liquid ammonia (0.7 l) using a catalyst, hydrated ferric nitrate (0.1 g). Then a solution of sodium acetylide in liquid ammonia was prepared by passing acetylene into the solution of sodamide at −35 °C for 4—5 h. Epichlorohydrin (55.5 g) was added during 2 h to the stirred solution of sodium acetylide and stirring was continued overnight at −70 °C. Ammonium chloride (66.0 g) was added during 2.5 h to this black viscous solution. The reaction mixture was warmed to expel ammonia and the residue was extracted with ether (400 ml). The ethereal solution was filtered and the solid dissolved in water. The aqueous solution was extracted with ether (2 × 100 ml), washed, and then dried (Na_2SO_4). Removal of the solvent from this solution gave a deep yellow oil (37.1 g) which was distilled under nitrogen at reduced pressure to give a mixture (13.2 g, 27%) of the *trans* (35) and *cis* (36) isomers, which g.l.c. (80 °C) indicated were present in the ratio 67 : 33, respectively. The two isomers were separated by preparative g.l.c. on a Carbowax 20 M column at 90 °C to afford pure samples of (*E*)-1-hydroxypent-2-en-4-yne (35) [Found: *M* (mass spec.), 82; C, 71.5; H, 7.5. Calc. for C_5H_6O: *M*, 82; C, 73.2; H, 7.3%]; δ($CDCl_3$; 220 MHz) 6.32 (1 H, d × t, $J_{1,2}$ 3.4 Hz, $J_{2,3}$ 15.9 Hz, 2-H), 5.70 (1 H, d × t × d, $J_{1,3}$ 2.4 Hz, $J_{2,3}$ 15.9 Hz, $J_{3,5}$ 1.2 Hz, 3-H), 4.18 (2 H, d × d, $J_{1,2}$ 5.4 Hz, $J_{1,3}$ 2.4 Hz, 2 × 1-H), 2.86 (1 H, d, $J_{3,5}$ 1.2 Hz, 5-H), and 2.46 (1 H, bs, OH); and (*Z*)-1-hydroxypent-2-en-4-yne (36) [Found *M* (mass spec.), 82; C, 72.3; H, 7.2. Calc. for $C_5H_6O_7$: *M*, 82; C, 73.2; H, 7.3%); δ ($CDCl_3$; 220 MHz) 6.15 (1 H, d × t, $J_{1,2}$ 5.0 Hz, $J_{2,3}$ 11.0 Hz, 2-H), 5.55 (1 H, d × d, $J_{2,3}$ 11.0 Hz, $J_{3,5}$ 1.0 Hz, 3-H), 4.37 (2 H, d × d, $J_{1,2}$ 5.0 Hz, $J_{1,3}$ 1.5 Hz, 2 × 1-H), 3.18 (1 H, s, 5-H), and 2.90 (1 H, s, OH).

rel-(3S,4R)-3,4,5-*Triacetoxypent*-2-*yne* (37).—The *cis*-hydroxypentenyne (36) (1.0 g, 12.8 mmol) was added to formic acid (98%, 5.6 g, 122 mmol) and this mixture was treated with hydrogen peroxide (100 vol; 2.2 g, 18.3 mmol). The reaction mixture was maintained at 50 °C overnight, water (1 ml) was added, and heating was continued for a further 3 h. On cooling, the excess of peroxide was destroyed by shaking this solution with sodium thiosulphate (2.8 g, 11.3 mmol). The suspension was filtered and water was added

to the filtrate. This pale yellow solution was shaken with calcium hydroxide (9.5 g) until neutral. The solid was filtered off and water was removed from the filtrate under reduced pressure to give a pale yellow oil (1.0 g) which was distilled at 0.5 mmHg to afford a clear yellow liquid between 170 and 190 °C. This product in acetic anhydride (10 ml) was added to a solution of potassium acetate (8 mg) in acetic anhydride (0.4 ml) and the reaction mixture was refluxed for 3 h, then cooled. Water was added and the aqueous solution was extracted with ether; the ethereal solution was washed and then dried (Na_2SO_4). The solvent was removed under reduced pressure to yield an oil which was characterised as *rel*-(3*S*,4*R*)-3,4,5-triacetoxypent-2-yne (37) (156 mg, 0.65 mmol, 5.1%) [Found: (M − 97) (mass spec.), 145. Calc. for $C_{11}H_{14}O_6$: M, 242]; δ ($CDCl_3$; 220 MHz) 5.55 (1 H, d × d, $J_{2,3}$ 6.4 Hz, $J_{3,5}$ 2.2 Hz, 3-H), 5.31—5.18 (1 H, m, 2-H), 4.41 (1 H, d × d, J_{gem} 12.0 Hz, $J_{1,2}$ 3.6 Hz, 1-H), 4.20 (1 H, d × d, J_{gem} 12.0 Hz, $J_{1,2}$ 5.6 Hz, 1-H), 2.51 (1 H, d, $J_{3,5}$ 2.2 Hz, 5-H), and 2.12 and 2.08 (9 H, 2 × s in the ratio of 2 : 1, 3 × OAc).

Method A. rel-(3R,4R)-3,4,5-*Triacetoxypent*-1-*ene* (34). The acetoxyepoxypentene (33) (0.54 g, 3.80 mmol) was added to a solution of tetra-n-butylammonium acetate (0.12 g, 0.4 mmol) in acetic anhydride (0.8 ml) and the reaction mixture was heated at 90 °C overnight, then cooled to room temperature. Ether was added to the reaction mixture and the ethereal solution was washed and then dried (Na_2SO_4). The solvent was removed under reduced pressure and the residual oil (0.82 g) was distilled at 135 °C at 0.01—0.02 mmHg. The colourless distillate was characterised as *rel*-(3*R*,4*R*)-3,4,5-triacetoxypent-1-ene (34) (0.56 g, 2.30 mmol, 60%) [Found: (M − 59) (mass spec.), 185; C, 53.2; H, 6.6. Calc. for $C_{11}H_{16}O_6$: M, 244; C, 54.1; H, 6.6%]; δ ($CDCl_3$; 220 MHz) 5.69 (1 H, m, 2-H), 5.40 (1 H, t, $J_{2,3}$ 6.1 Hz, $J_{3,4}$ 6.1 Hz, 3-H), 5.39—5.14 (3 H, m, 4-H and 2 × 1-H), 4.26 (1 H, d × d, J_{gem} 11.0 Hz, $J_{4,5}$ 3.7 Hz, 5-H), 4.00 (1 H, d × d, J_{gem} 11.0 Hz, $J_{4,5}$ 7.3 Hz, 5-H), and 2.09, 2.07, and 2.05 (9 H, 3 × s, 3 × OAc).

Method B. The triacetoxypentyne (37) (156 mg, 0.65 mmol) was added to a suspension of palladium (5%) on calcium carbonate in ethyl acetate (1.3 ml). This mixture was stirred under hydrogen until the uptake (43.5 ml) of the gas ceased. The catalyst was filtered off and the filtrate was concentrated to yield a pale yellow oil which was shown to be identical with the triacetoxypentene (34) (100 mg, 63%) synthesised from the acetoxyepoxypentene (33).

rel-(2R,3R,4S)-1,2,3-*Triacetoxy*-4,5-*epoxypentane* (39).—A solution of peroxytrifluoroacetic acid in dichloromethane (2.0 ml containing 5.5 mmol CF_3CO_3H) was added gradually to a refluxing stirred suspension of the triacetoxypentene (34) (0.56 g, 2.3 mmol) and freshly dried and powdered disodium hydrogen phosphate (1.4 g, 10.0 mmol) in dichloromethane (5.0 ml). The reaction was monitored by g.l.c. (200 °C). The reaction mixture was then cooled down to room temperature, additional dichloromethane (5 ml) was added, and the solid was filtered off. The filtrate was washed and then dried (Na_2SO_4). The solvent was removed under reduced pressure to give a colourless oil which was purified by h.p.l.c. on silica with ethyl acetate–hexane (1 : 9) as eluant to afford *rel*-(2*R*,3*R*,4*S*)-1,2,3-triacetoxy-4,5-epoxypentane (39) (0.4 g, 1.5 mmol, 67%) (Found: C, 49.9; H, 6.1. Calc. for $C_{11}H_{16}O_7$: C, 50.8; H, 6.2%); δ ($CDCl_3$; 220 MHz) 5.38—5.15 (1 H, m, 2-H), 5.02 (1 H, t, $J_{2,3}$ 5.1 Hz, $J_{3,4}$ 5.1 Hz, 3-H), 4.40 (1 H, J_{gem} 12.2 Hz, $J_{1,2}$ 4.2 Hz, 1-H), 4.10 (1 H, d × d, J_{gem} 12.2 Hz, $J_{1,2}$ 6.1 Hz, 1-H), 3.03—3.14 (1 H, m, 4-H), 2.83 (1 H, t, J_{gem} 4.9 Hz, $J_{4,5}$ 4.9 Hz, 5-H *cis* to 4-H), 2.64 (1 H, d × d, J_{gem} 4.9 Hz, $J_{4,5}$ 2.4 Hz, 5-H *trans* to 4-H), and 2.09, 2.06, and 2.00 (9 H, 3 × s, 3 × OAc).

Xylitol Penta-acetate (16).—*Method A.* The triacetoxyepoxypentane (39) (0.40 g, 1.54 mmol) was added to a solution of tetra-n-butylammonium acetate (0.05 g, 0.154 mmol) in acetic anhydride (0.82 ml, 4.0 mmol) and the reaction mixture was heated at 90 °C overnight. The reaction was monitored by g.l.c. (180 °C) and after 16 h reaction was complete with the only products being xylitol penta-acetate (16) and DL-arabinitol penta-acetate DL-(15) in the ratio 78 : 22, respectively. The reaction mixture was cooled down to room temperature, and chloroform was then added and the solution was washed and then dried (Na_2SO_4). The solvent was removed under reduced pressure to afford an oil (0.41 g) which crystallised on addition of methanol. Recrystallisation of the crude solid from methanol gave xylitol penta-acetate (16) (0.166 g, 0.46 mmol, 30%), m.p. 52—58 °C (lit.,[46] m.p. 61.5—62.5 °C) (Found: C, 49.2; H, 6.2. Calc. for $C_{15}H_{22}O_{11}$: C, 49.7; H, 6.1%); δ ($CDCl_3$; 220 MHz) 5.36 (1 H, t, $J_{2,3}$ = $J_{3,4}$ 6.0 Hz, 3-H), 5.28—5.16 (2 H, m, 2-H and 4-H), 4.21 (2 H, d × d, J_{gem} 12.0 Hz, $J_{1,2}$ = $J_{4,5}$ 5.0 Hz, 1-H and 5-H), 3.95 (2 H, d × d, J_{gem} 12.0 Hz, $J_{1,2}$ = $J_{4,5}$ 6.0 Hz, 1-H and 5-H), and 2.20, 2.16, and 2.12 (15 H, 3 × s, 3 × OAc); δ (^{13}C) ($CDCl_3$) 170.0, 169.6, and 169.3 (CO), 69.0 (CH), 61.7 (CH_2), and 20.7 and 20.5 p.p.m. (CO*Me*).

Method B. A mixture (136 mg, 0.52 mmol) of isomers A (13) and B (14) was added to a solution of tetra-n-butylammonium acetate (8 mg, 0.04 mmol) in acetic anhydride (2.7 ml). This reaction mixture was maintained at 120 °C and the reaction was monitored by g.l.c. (180 °C). After 79 h, ether was added to the cooled solution and the ethereal solution was washed and then dried (Na_2SO_4). Removal of the solvent gave an oil (112 mg) which was purified by column chromatography on silica with ethyl acetate–light petroleum (b.p. 60—80 °C) (3 : 7) as eluant to afford xylitol penta-acetate (16) (39 mg, 0.11 mmol, 21%), m.p. 58—60 °C (lit.,[46] m.p. 61.5—62.5 °C).

Method C. G.l.c. analysis indicated that when a few crystals of compound (Z) (23) were treated with acetic anhydride (4 drops) at 112 °C, conversion into xylitol penta-acetate (16) with greater than 98% stereoselectivity was complete within 2 h. The very small amount of arabinitol penta-acetate DL-(15) revealed by the g.l.c. analysis probably reflects the presence of isomer A (13) as an impurity in the crystals.

DL-*Arabinitol Penta-acetate* DL-(15) *and Xylitol Penta-acetate* (16).—A solution of peroxytrifluoroacetic acid in dichloromethane (0.18 ml containing 0.5 mmol CF_3CO_3H) was added to a refluxing stirred suspension of the acetoxyepoxypentene (33) (50 mg, 0.35 mmol) and disodium hydrogen phosphate (210 mg, 1.4 mmol) in dichloromethane (1.5 ml). G.l.c. analysis (180 °C) indicated the reaction was complete after 110 min. Dichloromethane was then added to the cooled reaction mixture and the solution was washed and then dried (Na_2SO_4). The crude product which was isolated from this solution was treated with tetra-n-butylammonium acetate in acetic anhydride at 120 °C and the products examined by g.l.c. (180 °C). This analysis indicated that DL-arabinitol penta-acetate DL-(15) and xylitol penta-acetate (16) were present in the ratio 47 : 53, respectively.

Acknowledgements

We thank Dr. W. Hewertson (I.C.I. Corporate Laboratory) for his interest, and the S.E.R.C. for a Co-operative Research Scheme Award (to J. F. S.) and a C.A.S.E. Award (to D. H.). We also wish to thank Mr. I. Brown (I.C.I.) and Drs. B. E. Mann and C. M. Spencer (Sheffield) for determining some of the ^1H and ^{13}C n.m.r. spectra.

References

1 W. M. Nicol, *Chem. Ind.*, 1977, 427.
2 J. F. Stoddart, 'Stereochemistry of Carbohydrates,' Wiley-Interscience, New York, 1971, pp. 21—22.
3 J. F. Stoddart, in D. H. R. Barton and W. D. Ollis, 'Comprehensive Organic Chemistry,' ed. J. F. Stoddart, Pergamon Press, Oxford, 1979, vol. 1, pp. 3—33.
4 H. E. Ramsden, J. R. Leebrick, S. D. Rosenberg, E. H. Miller, J. J. Walburn, A. E. Balint, and R. Cserr, *J. Org. Chem.*, 1957, **22**, 1602.
5 E. E. Boehm and M. C. Whiting, *J. Chem. Soc.*, 1963, 2541.
6 L. Crombie, S. H. Harper, and D. Thompson, *J. Chem. Soc.*, 1951, 2906.
7 D. Holland and J. F. Stoddart, *Carbohydry. Res.*, 1982, **100**, 207.
8 P. Chautemps, *C. R. Acad. Sci., Ser. C*, 1977, **284**, 807.
9 R. Lespieau, *Adv. Carbohydr. Chem.*, 1946, **2**, 107.
10 R. A. Raphael, *J. Chem. Soc.*, 1949, S44.
11 D. Holland and J. F. Stoddart, *Tetrahedron Lett.*, 1982, 5367.
12 K. H. Schulte-Elte, B. Willhalm, and G. Ohloff, *Angew. Chem., Int. Ed. Engl.*, 1969, **8**, 985.
13 W. R. Adams and D. J. Trecker, *Tetrahedron*, 1971, **27**, 2631.
14 G. Ohloff, *Pure Appl. Chem.*, 1975, **43**, 481.
15 G. Wilkinson, 'Organic Synthesis, Coll. Vol. IV,' 1963, 473.
16 J. G. Buchanan and H. Z. Sable, in 'Selective Organic Transformations,' ed. B. S. Thyagarajan, Wiley-Interscience, New York, 1972, vol. 2, p. 1.
17 C. J. M. Stirling, *Chem. Rev.*, 1978, **78**, 517.
18 J. E. Baldwin, *J. Chem. Soc., Chem. Commun.*, 1976, 734; and in 'Further Perspectives in Organic Chemistry,' Ciba Foundation Symposium 53, Elsevier, Amsterdam, 1978, p. 85.
19 R. U. Lemieux, in 'Molecular Rearrangements,' ed. P. de Mayo, Wiley-Interscience, New York, 1963, p. 713.
20 E. D. Mihelich, *Tetrahedron Lett.*, 1979, 4729.
21 B. Capon, *Quart. Rev.*, 1964, **18**, 45; *Chem. Rev.*, 1969, **69**, 407.
22 K. B. Sharpless and K. Akashi, *J. Am. Chem. Soc.*, 1976, **98**, 1986; K. Akashi, R. E. Palermo, and K. B. Sharpless, *J. Org. Chem.*, 1978, **43**, 2063.
23 B. G. Yashnitskii, S. A. Sarkisyants, and E. G. Ivanuk, *Zh. Obshch. Khim.*, 1964, **34**, 1940.
24 D. H. Williams and I. Fleming, 'Spectroscopic Methods in Organic Chemistry,' McGraw-Hill, London, 3rd edn, 1980.
25 J. G. Buchanan and A. R. Edgar, *Carbohydr. Res.*, 1969, **10**, 295.
26 K. B. Sharpless and T. R. Verhoeven, *Aldrichimica Acta*, 1979, **12**, 63.
27 K. B. Sharpless and R. C. Michaelson, *J. Am. Chem. Soc.*, 1973, **95**, 6136.
28 S. Tanaka, H. Yamamoto, H. Nozaki, K. B. Sharpless, R. C. Michaelson, and J. D. Cutting, *J. Am. Chem. Soc.*, 1974, **96**, 5254.
29 B. E. Rossiter, T. R. Verhoeven, and K. B. Sharpless, *Tetrahedron Lett.*, 1979, 4733.
30 E. D. Mihelich, K. Daniels, and D. J. Eickhoff, *J. Am. Chem. Soc.*, 1981, **103**, 7690.
31 K. Takai, K. Oshima, and H. Nozaki, *Tetrahedron Lett.*, 1980, **21**, 1657.
32 H. Tomioka, T. Suzuki, K. Oshima, and H. Nozaki, *Tetrahedron Lett.*, 1982, **23**, 3387.
33 M. Isobe, M. Kitamura, S. Mio, and T. Goto, *Tetrahedron Lett.*, 1982, **23**, 221.
34 R. P. Heggs and B. Ganem, *J. Am. Chem. Soc.*, 1979, **101**, 2484.
35 K. Sonogashira, Y. Tohda, and N. Hagihara, *Tetrahedron Lett.*, 1975, 4467.
36 L. Crombie, S. H. Harper, T. C. Newman, D. Thompson, and R. J. D. Smith, *J. Chem. Soc.*, 1956, 126.
37 N. Minami, S. S. Ko, and Y. Kishi, *J. Am. Chem. Soc.*, 1982, **104**, 1109.
38 W. R. Roush and R. J. Brown, *J. Org. Chem.*, 1982, **47**, 1371.
39 T. Katsuki, A. W. M. Lee, P. Ma, V. S. Martin, S. Masamune, K. B. Sharpless, D. Tuddenham, and F. J. Walker, *J. Org. Chem.*, 1982, **47**, 1373.
40 P. Ma, V. S. Martin, S. Masamune, K. B. Sharpless, and S. M. Viti, *J. Org. Chem.*, 1982, **47**, 1378.
41 J. M. Finan and Y. Kishi, *Tetrahedron Lett.*, 1982, **23**, 2719.
42 T. Katsuki and K. B. Sharpless, *J. Am. Chem. Soc.*, 1980, **102**, 5976; B. E. Rossiter, T. Katsuki, and K. B. Sharpless, *J. Am. Chem. Soc.*, 1981, **103**, 464; V. S. Martin, S. S. Woodard, T. Katsuki, Y. Yamada, M. Ikeda, and K. B. Sharpless, *J. Am. Chem. Soc.*, 1981, **103**, 6237; A. W. M. Lee, V. S. Martin, S. Masamune, K. B. Sharpless, and F. J. Walker, *J. Am. Chem. Soc.*, 1982, **104**, 3515; K. B. Sharpless, C. H. Behrens, T. Katsuki, A. W. M. Lee, V. S. Martin, M. Takatani, S. M. Viti, F. J. Walker, and S. S. Woodard, *Pure Appl. Chem.*, 1983, **55**, 589.
43 J. C. Sowden, *J. Am. Chem. Soc.*, 1951, **73**, 5496; C. L. Mehltretter, B. H. Alexander, R. L. Mellies, and C. E. Rist, *J. Am. Chem. Soc.*, 1951, **73**, 2424; V. F. Pfeifer, V. E. Sohns, H. F. Conway, E. B. Lancaster, S. Dabic, and E. L. Griffin, Jr., *Ind. Eng. Chem.*, 1960, **52**, 201; J. Kiss, R. D'Sonza, and P. Taschner, *Helv. Chim. Acta*, 1975, **58**, 311; P. P. Singh, M. M. Gharia, F. Dasgupta, and H. C. Srivastava, *Tetrahedron Lett.*, 1977, 439.
44 *Chem. Ind.*, 1977, 239; *Chem. Eng. News*, 1977, 22.
45 *The Morning News*, Wilmington, Delaware, Nov. 16, 1977, p. 35; *Wall Street Journal*, Nov. 16, 1977, p. 1; *The Evening Bulletin*, Philadelphia, Pennsylvania, Nov. 16, 1977, p. 12; *Food Chemical News*, Sept. 4, 1978, p. 33; Nov. 13, 1978, p. 23.
46 'Dictionary of Organic Compounds,' Eyre and Spottiswoode, London.
47 H. O. House and G. H. Rasmusson,, *J. Org. Chem.*, 1961, **26**, 4278.
48 C. R. Davies and J. S. Davies, *J. Chem. Soc., Perkin Trans. 1*, 1976, 2390.
49 H. B. Henbest and R. Nicholls, *J. Chem. Soc.*, 1957, 4608.

Received 25*th October* 1982; *Paper* 2/1807