Phase-Transfer Synthesis of Optically Pure Oxetanes Obtained from 1,2,2-Trisubstituted 1,3-Propanediols

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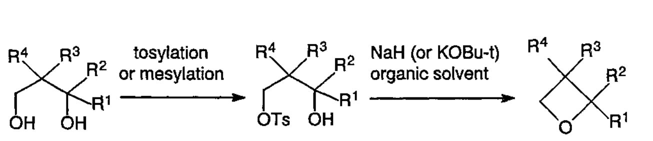
Treatment of the 3-monomethanesulfonates of 1,2,2-trisubstituted 1,3-propanediols under phase-transfer conditions affords 2-aryl (or alkyl)-3,3-dialkyloxetanes. Twelve oxetanes have been obtained by this method; three of these oxetanes have been obtained enantiomerically pure as both enantiomers starting from the appropriate enantiomerically pure 1,3-diols. In these reactions the chiral center does not undergo inversion and the oxetanes have the same absolute configuration as the starting 1,3-diols.

The development of various ring-opening and ring-expansion strategies has increased the synthetic accessibility of oxetanes. This, together with some commercial successes in polymers, pharmaceuticals and agrochemicals has led to renewed interest in these ring systems.[1-14] Oxetanes are often synthesized from 1,3-diols by treatment of their methanesulfonates or toluenesulfonates under alkaline conditions (sodium hydride, potassium *tert*-butoxide, butyllithium, etc.) in organic solvents (Scheme 1).[15-17] This method suffers sometimes, however, from low yields as well as the need for expensive alkaline reagents, which makes the procedure less attractive to apply, particularly in an industrial setting.

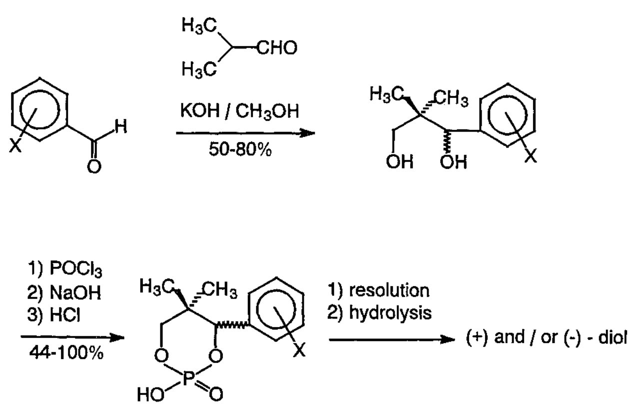


Scheme 1

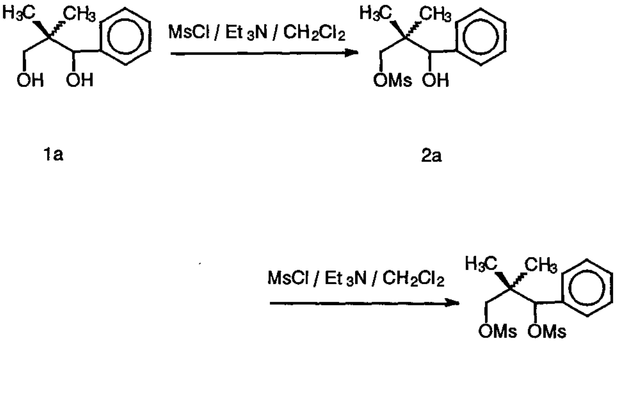
Trisubstituted 1,3-propanediols are easily obtained from an aldol condensation followed by a cross Cannizzaro reaction when two equivalents of isobutyraldehyde (or another α,α-disubstituted aliphatic aldehyde) and a substituted benzaldehyde (or in some cases an aliphatic aldehyde) are allowed to react under basic conditions in alcoholic solvents.[18-19] These 1,3-diols are interesting in that they are readily converted to phosphoric acid derivatives on reaction with phosphorous oxychloride followed by base. These phosphoric acids have been resolved by ten Hoeve and Wynberg.[20] The enantiomerically pure 1,3-diols can be readily obtained by treatment of the phosphoric acids with glycol and potassium hydroxide or with lithium aluminum hydride (Scheme 2).[21] There has been considerable interest in using these enantiomerically pure 1,3-diols as chiral synthons or chiral auxiliaries.[22-23]

Synthesis and stereochemical characterization of both racemic and optically pure oxetanes from these 1,3-diols was the aim of this work.

Reaction of the diols **1a–i**, obtained as indicated in Scheme 2, with methanesulfonyl chloride at – 10 to 0 °C in the presence of triethylamine or pyridine in dichloromethane or chloroform gave the sensitive monomethanesulfonates **2a–i**, which could be characterized by NMR techniques. There is ample precedent for mesylation (or tosylation) at the least hindered primary hydroxy group.[24-28] This structural assignment is also entirely consistent with the ^{1}H NMR spectrum. For **2a** the benzylic proton, which is diagnostic for functionalization at the secondary hydroxy group, absorbs at $\delta = 4.65$ and is barely shifted relative to the free diol **1a** in which this absorption is found at $\delta = 4.62$. The diastereotopic protons of the methylene group are, however, shifted downfield in **2a**. In the dimesylate **5**, obtained by mesylation with excess mesyl chloride under forcing conditions, the benzylic proton is shifted downfield to $\delta = 5.50$ indicative of mesylation at this position. The conversions are illustrated for the series **a** in Scheme 4. No evidence (NMR) was ever obtained for competing sulfonation at the secondary alcohol position.

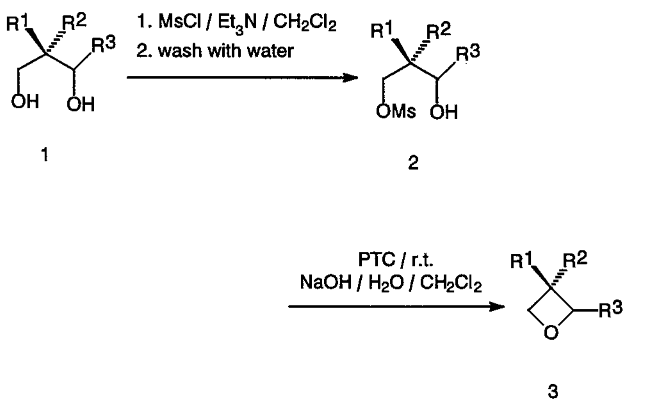


Scheme 2



Scheme 3

Ring closure is accomplished under basic conditions in a Williamson reaction whereby the secondary alcohol acts as the nucleophile. Phase transfer catalysis (PTC) offers significant advantages over conventional procedures for ionic substitution processes.[29] The avoidance of expensive anhydrous or aprotic solvents, the use of cheap, aqueous bases, improved reaction rates, lower reaction temperatures, and easier workup are all advantages that accrue to the method. Application of PTC methods (quaternary ammonium salt, NaOH as base, CH_2Cl_2 as solvent) led to the formation of **3a–i** (Scheme 4) in the overall yields indicated in parentheses.



a R^1=R^2=CH_3, R^3=C_6H_5, (96%);
b R^1=R^2=CH_3, R^3=2-FC_6H_4, (92%);
c R^1=R^2=CH_3, R^3=2-ClC_6H_4, (92%);
d R^1=R^2=CH_3, R^3=4-ClC_6H_4, (94%);
e R^1=R^2=CH_3, R^3=2-BrC_6H_4, (90%);
f R^1=R^2=CH_3, R^3=2-$NO_2C_6H_4$, (90%);
g R^1=R^2=CH_3, R^3=2-$CH_3OC_6H_4$, (92%);
h R^1=R^2=CH_3, R^3=4-$CH_3OC_6H_4$, (93%);
i R^1=R^2=CH_3, R^3=2-$CH_2CH_3OC_6H_4$, (91%);
j R^1=R^2=CH_3, R^3=$CHMe_2$, (95%);
k R^1=R^2=CH_3, R^3=Thienyl, (85%);
l R^1=R^2=Cyclohexylidine, R^3=C_6H_5, (87%);

Scheme 4

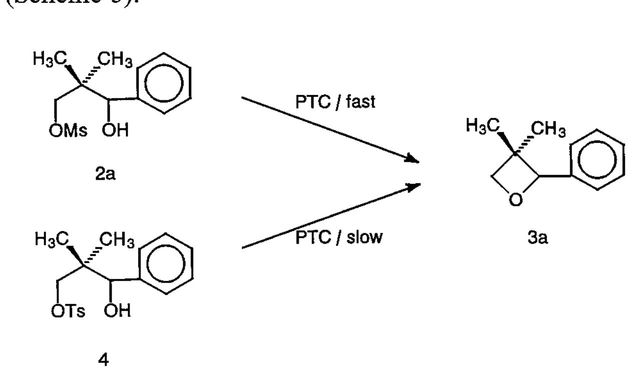
Compound **3a** has been reported in the literature[15] and was prepared in 82% yield from the mesylate of **1a** by treatment with KOBu-*t* in *tert*-butyl alcohol following the literature method. Attempts by us (entries 2 and 3 in Table 1) to use cheaper KOH in MeOH led to significantly poorer yields. The 2-methyl-1-phenylprop-1-ene found (entry 3) appears to be the result of a catalyzed thermolysis of mesylate **2a** or oxetane **3a** at 50 °C. The pure oxetanes are, however, thermally stable at this temperature and begin to undergo thermal cycloreversion and/or polymerization only at about 300 °C.[30] Oxetane thermolysis is complicated and is known to be subject to acid catalysis.[31,32] On distillation of impure **3a** containing a very small amount of mesylate (monomesylate or dimesylate) some 2-methyl-1-phenylprop-1-ene was observed, apparently the result of catalyzed decomposition. The oxetanes were therefore first subjected to column chromatography followed by distillation to obtain analytically pure materials.

Table 1. Ring Closure of **2a** Under Various Conditions to Give Compound **3a** (Scheme 5).

Entry	Reaction conditions	Yield (%)
1	*t*-BuOH/*t*-BuOK, r.t., 20 h	82
2	KOH/MeOH, r.t., 20 h	51
3	KOH/MeOH, 50 °C/1 h and then r.t./10 h	55[a]
4	PTC, CH_2Cl_2/H_2O/NaOH, r.t./2–4 h	>95

[a] 2-Methyl-1-phenylprop-1-ene formed in 38% yield.

The choice of leaving group is important. The tosylate of **1a** under comparable PTC conditions required a reaction time of five days at room temperature to obtain a yield of **3a** of 50% whereas **2a** provided the oxetane in > 95% yield in 2–4 hours under analogous conditions (Scheme 5).



Scheme 5

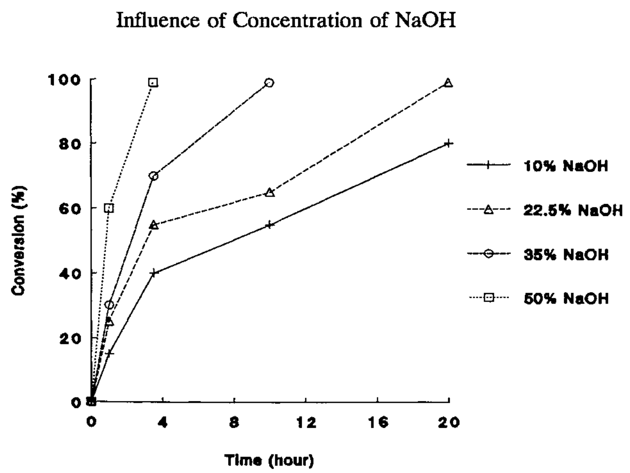
Several quaternary ammonium salts were examined as phase transfer catalysts under given conditions for the synthesis of **3a** from **2a** (Table 2). Bu_4NHSO_4 is clearly the best catalyst among these quaternary ammonium salts although Bu_4NBr, Bu_4NF and $(n\text{-}C_8H_{17})_3MeNCl$ are also acceptable under the conditions used.

Table 2. Influence of PTC[a] on the Ring Closure of **2a** (Scheme 5).

Entry	PTC	Results[b, c]
1	Bu_4NBr	++
2	Bu_4NI	+
3	Bu_4NF	++
4	Bu_4NHSO_4	+++
5	Et_4NCl	+
6	$PhCH_2NEt_3Cl$	+
7	$PhCH_2NMe_3OH$	+
8	$(n\text{-}C_8H_{17})_3NMeCl$	++
9	No PTC	–

[a] Reaction condition: monomesylate **2a** (1 g), CH_2Cl_2 (30 mL), 10% aq NaOH (15 mL), PTC (1 mol%), stirring at r.t.
[b] The conversion of reactants was followed by NMR.
[c] –, Very slow, conversion about 35% after stirring for 5 d; +, some reaction, conversion about 65% after stirring for 2 d; ++, good, conversion about 80% after stirring for 18 h; +++, very good, conversion about 97% after stirring for 8 h.

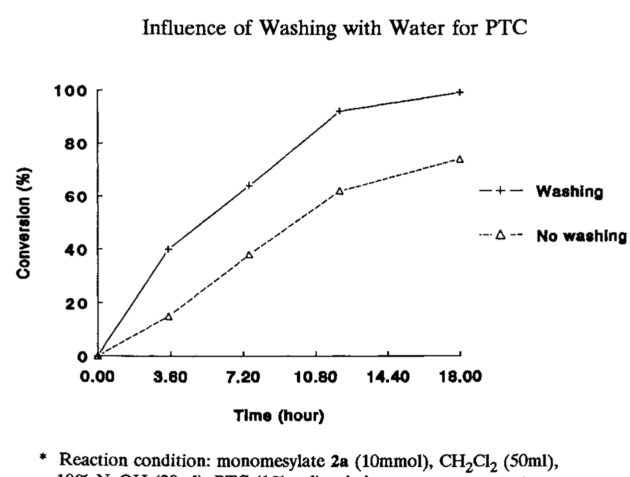
There is a roughly linear relation (at least in the initial stages) between the concentration of alkali and the reaction rate under standard conditions (Figure 1). Mesylate **2a** was converted to oxetane within 3–4 hours when 50% aqueous sodium hydroxide was used but the reaction took nearly one day when 10% aqueous sodium hydroxide was used.



* Reaction condition: monomesylate **2a** (1g), CH_2Cl_2 (20ml), NaOH in water (10ml), PTC (1%mol), stirring at the room temperature.
** Detected by NMR, the conversion of monomesylate **2a** was followed.

Figure 1

In phase transfer catalysis, the effect of counterions can be pronounced. In initial experiments, crude mesylates were used without purification for the ring-closure reactions in an attempt to carry out a one-pot procedure. As shown in Figure 2, however, extraction of the crude mesylate **2a**, dissolved in CH_2Cl_2, with H_2O prior to reaction leads to a substantial increase in reaction rate. This is most likely due to the removal of Et_3NH^+, Cl^- from the mesylate. This extra ionic material suppresses the rate of ring closure. A washing procedure was used consistently once this effect had been uncovered.



* Reaction condition: monomesylate **2a** (10mmol), CH_2Cl_2 (50ml), 10% NaOH (20ml), PTC (1%mol), stirring at room temperatue.
** Detected by NMR, the conversion of monomesylate **2a** was followed.

Figure 2

Table 3. Absolute $[\alpha]_{578}^{20}$ of Optically Pure Oxetanes[a]

Compound	Absolute $[\alpha]_{578}$ (*c*) ($CHCl_3$)
(*S*)-(+)-**3a**	+122.6 (0.45)
(*R*)-(−)-**3a**	−124.4 (0.45)
(*S*)-(−)-**3c**	−155.5 (0.38)
(*R*)-(+)-**3c**	+157.6 (0.42)
(*S*)-(−)-**3g**	−173.5 (0.37)
(*R*)-(+)-**3g**	+171.8 (0.38)

[a] The enantiomeric purity of the oxetanes was determined by ^{1}H NMR (200 MHz) analysis using the chiral shift reagent tris(d,d-dicampholylmethanato)europium(III), Eu(dcm)$_3$, 10 mol%.

Optically active 3,3-dimethyl-2-phenyl-oxetane (*S*)-(+)-**3a** has been synthesized previously by means of enantioselective reduction of 3-chloro-2,2-dimethyl-1-phenyl-1-propanone followed by ring closure.[33] In this work as well as that of Balsamo et al.[15] it has been shown that the chiral center of starting substances (1,2-disubstituted 1,3-diols or 1,2-disubstituted 3-chloropropanols) is not involved in the ring closure and keeps its original configuration. The diols **1a**, **1c** and **1g** in optically pure *R* and *S* forms were readily converted into the optically pure oxetanes (Figure 3) by the PTC procedure described above. The configuration of the asymmetric center is not affected during reaction. Optical rotations of the products are given in Table 3. Optically pure (*S*)-(+)-**3a** has an absolute rotation of $[\alpha]_D$ +113.8°, which agrees with literature data[33] [for (*S*)-(+)-**3a** of 89% ee an $[\alpha]_D$ +100.1° was found, corresponding to $[\alpha]_D$ +112.5° for optically pure material].

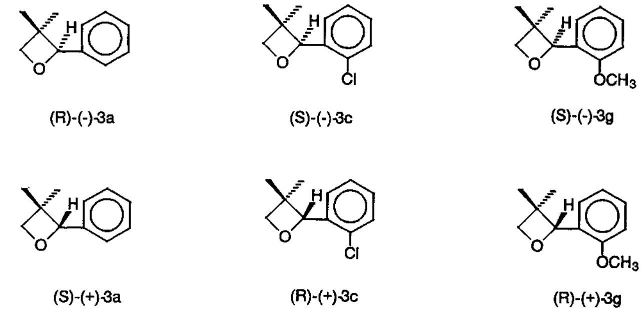


Figure 3

All chemicals used in this work were commercially available. The 1,3-diols including optically pure samples were prepared following literature methods.[20] (*S*)-(−)-2-Hydroxy-4-(2-methoxyphenyl)-5,5-dimethyl-1,3,2-dioxaphosphorinane 2-oxide was generously supplied by Dr. R. Hulst. 1-Isopropyl-2,2-dimethyl-1,3-propanediol was bought from Janssen as were all of the quaternary ammonium salts used as phase transfer catalysts. Methanesulfonyl chloride should be used from a fresh bottle. ^{1}H NMR (200 MHz) and ^{13}C NMR (50.3 MHz) spectra were determined on a Varian Gemini-200 system. $CDCl_3$ was used as a solvent and Me_4Si as an internal reference. The enantiomeric purities of the oxetanes were determined by ^{1}H NMR (200 MHz) analysis using the chiral shift reagent tris(dicampholylmethanato)europium(III), Eu(dcm)$_3$, 10 mol percent. In all cases the racemic mixtures were examined to ascertain whether the enantiomers could be discriminated. Accuracy is about 5%. IR spectra were obtained in KBr pellets with a Perkin-Elmer

781 spectrometer. Mass spectra were recorded on an AEI-MS902 mass spectrometer at 70 eV. All mps were determined on a Mettler FP1 melting apparatus and are uncorrected. Optical rotations were measured with a Perkin-Elmer Model 241 polarimeter at room temperature.

2,3-Substituted Oxetanes from 1,2-Substituted 1,3-Propanediols; General Procedure:
To a stirred solution of diol (0.1 mol) and dry Et_3N (0.12 mol) in CH_2Cl_2 (150 mL) at 0 °C was added dropwise a solution of methanesulfonyl chloride (0.105 mol) in CH_2Cl_2 (50 mL). The mixture was stirred at 0 °C for 30 min after the addition, then allowed to warm to r.t. and was stirred for a further 1 h. The mixture was washed with 200 mL of water. A small sample of monomethanesulfonate was obtained for characterization by drying and evaporation of a part of the organic phase. This was examined by NMR and infrared spectroscopy. In view of the sensitivity, no attempts were made to purify these intermediates further except **2a**, which was crystallized by slow evaporation of solvent (CH_2Cl_2).

The organic phase was placed in a flask after separation of water. The phase transfer catalyst (PTC) (1–3 mol%) and 50 % aq NaOH (60 mL) was added. The mixture was stirred for 2–4 h at r.t. No monomethanesulfonate could be detected by TLC (aluminum oxide, Et_2O as eluant). The reaction was stopped and was worked up. The organic phase was separated and dried ($MgSO_4$). The solution was filtered and evaporated with a rotatory evaporator under reduced pressure. The residue was separated by column chromatography (aluminum oxide; Et_2O).[34] The pure oxetanes were obtained by bulb-to-bulb distillation under reduced pressure.

1,3-Dimethanesulfonyloxy-2,2-dimethyl-1-phenylpropane (5):[35]
To a stirred solution of 2,2-dimethyl-1-phenyl-1,3-propanediol (10 g, 55.6 mmol) in dry Et_3N (25 mL) and CH_2Cl_2 (100 mL) at 0 °C was slowly added dropwise methanesulfonyl chloride (13 mL, 167 mmol). The mixture was stirred at 0 °C for 30 min after the addition, then was stirred overnight at reflux temperature under a nitrogen atmosphere. The reaction mixture was poured into 150 mL of ice-water. The oil was extracted with $CHCl_3$ (× 3) and dried ($MgSO_4$). Evaporation of the solvent gave the product **5**, which was crystallized from Et_2O (17.0 g, 50.6 mmol, 91 % yield, mp: 83–86 °C).

^{1}H NMR ($CDCl_3$): δ = 0.95 (s, 3 H), 1.08 (s, 3 H), 2.65 (s, 3 H), 3.07 (s, 3 H), 3.92 (d, ^2J = 9.4 Hz, 1 H), 4.17 (d, ^2J = 9.4 Hz, 1 H), 5.51 (s, 1 H), 7.39 (m, 5 H).

^{13}C NMR ($CDCl_3$): δ = 19.11 (q), 21.04 (q), 37.18 (q), 39.12 (q), 39.30 (s), 74.16 (t), 86.09 (d), 127.92 (d), 128.50 (d), 29.19 (d), 134.55 (s).

IR (KBr): ν = 3425 br w, 3038 s, 3023 s, 2985 s, 2943 s, 1472 s, 1452 s, 1345 br vs, 1185 vs, 968 br vs, 842 vs, 748 s, 705 s cm^{-1}.

3,3-Dimethyl-2-phenyloxetane (3a) from 2,2-Dimethyl-1-phenyl-1,3-propanediol (1a) by Reaction of the Monomethanesulfonate with Potassium *tert*-Butoxide in *tert*-Butyl Alcohol:
A solution of the monomethanesulfonate **2a** (10 g, 55.6 mmol) in *t*-BuOH (120 mL) was treated with KOBu-*t* (7 g, 62.5 mmol) and was stored overnight at r.t. The reaction mixture was diluted with petroleum ether and filtered. Evaporation of the solvent gave a residue, which was washed with 30 mL of water and dried ($MgSO_4$). Filtration and evaporation gave crude oxetane (7.9 g). The crude product was separated by column chromatography (aluminum oxide; Et_2O) to yield 7.4 g (45.7 mmol, 82 %) of **3a**.

Reaction of 3-Methanesulfonyloxy-2,2-dimethyl-1-phenyl-1-propanol (2a) with Sodium Hydroxide (or Potassium Hydroxide) in Methanol:
The monomethanesulfonate **2a** (4 g, 15.5 mmol) was treated with KOH (3 g, 54 mmol) in MeOH (10 mL) and was left overnight at r.t. Isolation of the mixture gave 1.4 g (56 %) of 3,3-dimethyl-2-phenyloxetane and 1.7 g of starting monomethanesulfonate.

The monomethanesulfonate of 2,2-dimethyl-1-phenyl-1,3-propanediol (4 g, 15.5 mmol) was treated with KOH (3 g, 54 mmol) in MeOH (15 mL) and stirred for 1 h at 50 °C, and then stored overnight at r.t. The results of NMR measurements showed that the mixture contained 2-methyl-1-phenylprop-1-ene (38 %) and 3,3-dimethyl-2-phenyloxetane (55 %). No starting monomethanesulfonate was found.

3-Methanesulfonyloxy-2,2-dimethyl-1-phenyl-1-propanol (2a):
Mp 43–45 °C.

^{1}H NMR ($CDCl_3$): δ = 0.91 (s, 3 H), 0.93 (s, 3 H), 2.21 (s, 1 H), 3.02 (s, 3 H), 3.90 (s, 3 H), 3.92 (d, ^2J = 9.3 Hz, 1 H), 4.34 (d, ^2J = 9.3 Hz, 1 H), 4.65 (s, 1 H), 7.32 (t, 5 H).

^{13}C NMR ($CDCl_3$): δ = 18.34 (q), 21.47 (q), 36.89 (q), 39.70 (s), 76.13 (t), 76.58 (d), 127.61 (d), 127.76 (d), 127.84 (d), 140.07 (s).

IR (KBr): ν = 3539 br s, 3029 m, 2976 s, 1474 s, 1452 s, 1350 vs, 1172 vs, 1048 s, 957 vs, 831 s, 737 s, 705 s cm^{-1}.

3,3-Dimethyl-2-phenyloxetane (3a):[32]
^{1}H NMR ($CDCl_3$): δ = 0.82 (s, 3 H), 1.42 (s, 3 H), 4.28 (d, ^2J = 5.4 Hz, 1 H), 4.55 (d, ^2J = 5.4 Hz, 1 H), 5.54 (s, 1 H), 7.33 (m, 5 H).

^{13}C NMR ($CDCl_3$): δ = 22.41 (q), 26.89 (q), 40.25 (s), 81.24 (t), 91.72 (d), 125.06 (d), 127.25 (d), 128.08 (d), 140.00 (s).

IR (KBr): ν = 3440 br w, 3061 w, 3027 w, 2958 vs, 1721 m, 1461 m, 1271 m, 982 vs, 741 s, 700 s cm^{-1}.

Exact mass for $C_{11}H_{14}O$ requires: M, 162.104; found: M^+, 162.104.

2,2-Dimethyl-1-phenyl-3-toluenesulfonyloxy-1-propanol (4):
^{1}H NMR ($CDCl_3$): δ = 0.81 (s, 3 H), 0.85 (s, 3 H), 2.49 (s, 3 H), 3.51 (2d, 2 H), 3.92 (br, 3 H, H_2O), 4.62 (s, 1 H), 7.31–7.94 (m, 9 H).

^{13}C NMR ($CDCl_3$): δ = 18.84 (q), 22.73 (q), 39.02 (s), 71.97 (t), 82.02 (d), 127.00 (d), 127.44 (d), 127.58 (d), 127.67 (d), 127.92 (d), 130.22 (d), 141.44 (s), 146.80 (s), 157.90 (s).

IR (KBr): ν = 3412 br s, 3065 m, 3031 m, 2971 s, 2877 m, 1595 m, 1453 s, 1371 br s, 1173 vs, 1043 s, 966 s, 814 s, 704 s cm^{-1}.

1-(2-Fluorophenyl)-3-methanesulfonyloxy-2,2-dimethyl-1-propanol (2b):
^{1}H NMR ($CDCl_3$): δ = 0.90 (s, 6 H), 2.86 (br, 1 H), 3.00 (s, 3 H), 3.94 (d, ^2J = 9.3 Hz, 1 H), 4.34 (d, ^2J = 9.3 Hz, 1 H), 5.00 (s, 1 H), 7.23 (m, 4 H).

^{13}C NMR ($CDCl_3$): ν = 17.97 (q), 21.06 (q), 36.84 (q), 39.95 (s), 69.27 (d), 75.82 (t), 114.79 (d), 115.26 (d), 123.76 (d), 129.32 (d), 157.37 (s), 162.23 (s).

IR (KBr): ν = 3536 br s, 2972 s, 1600 s, 1586 m 1490 s, 1465 s, 1440 s, 1350 vs, 1286 m, 1241 s, 1173 vs, 1042 s, 955 s, 852 m, 833 m, 759 s cm^{-1}.

2-(2-Fluorophenyl)-3,3-dimethyloxetane (3b):
^{1}H NMR ($CDCl_3$): δ = 0.86 (s, 3 H), 1.45 (s, 3 H), 4.25 (d, ^2J = 5.4 Hz, 1 H), 4.54 (d, ^2J = 5.4 Hz, 1 H), 5.74 (s, 1 H), 6.95–7.64 (m, 4 H).

^{13}C NMR ($CDCl_3$): δ = 22.10 q, 26.20 q, 40.18 s, 81.35 s, 86.70 d, 114.24 d, 124.05 d, 126.94 d, 128.50 d, 156.64 s, 161.65 s.

IR (KBr): ν = 3432 br w, 3070 w, 2963 m, 2932 m, 1714 s, 1612 s, 1487 s, 1456 s, 1307 s, 1228 s, 1129 s, 1085 s, 757 s cm^{-1}.

Exact mass for $C_{11}H_{13}FO$ requires: M, 180.095; found: M^+, 180.095.

1-(2-Chlorophenyl)-3-methanesulfonyloxy-2,2-dimethyl-1-propanol (2c):
^{1}H NMR ($CDCl_3$): δ = 0.95 (s, 3 H), 0.96 (s, 3 H), 3.04 (s, 3 H), 3.99 (d, ^2J = 9.3 Hz, 1 H), 4.40 (d, ^2J = 9.3 Hz, 1 H), 5.25 (s, 1 H), 7.24–7.32 (m, 4 H).

^{13}C NMR ($CDCl_3$): δ = 18.05 q, 21.22 q, 37.00 q, 40.68 s, 71.33 d, 75.82 t, 126.46 d, 128.77 d, 129.33 d, 129.76 d, 133.28 s, 138.56 s.

IR (KBr): ν = 3535 br s, 3027 w, 2973 s, 1472 s, 1439 s, 1350 vs, 1174 vs, 1030 s, 957 vs, 851 s, 832 s, 754 s cm^{-1}.

2-(2-Chlorophenyl)-3,3-dimethyloxetane (3c):
^{1}H NMR ($CDCl_3$): δ = 0.85 (s, 3 H), 1.57 (s, 3 H), 4.29 (d, ^2J = 5.4 Hz, 1 H), 4.52 (d, ^2J = 5.4 Hz, 1 H), 5.78 (s, 1 H), 7.16–7.74 (m, 4 H).

^{13}C NMR ($CDCl_3$): δ = 22.03q, 26.93q, 40.33s, 81.24t, 89.00d, 126.74d, 127.28d, 128.17d, 128.84d, 130.80s, 138.03s.

IR (KBr): ν = 3437 br w, 3069 w, 2965 s, 2871 s, 1730 s, 1462 s, 1439 s, 1295 s, 1246 s, 1124 s, 1052 s, 987 s, 750 vs cm^{-1}.

Exact mass for $C_{11}H_{13}ClO$ requires: M, 196.065; found: M^+, 196.065.

1-(4-Chlorophenyl)-3-methanesulfonyloxy-2,2-dimethyl-1-propanol (2d):
^{1}H NMR ($CDCl_3$): δ = 0.87 (s, 3H), 0.89 (s, 3H), 3.03 (s, 3H), 3.88 (d, ^2J = 9.4 Hz, 1H), 4.33 (d, ^2J = 9.4 Hz, 1H), 4.63 (s, 1H), 7.26 (d, ^3J = 3.0 Hz, 2H), 7.31 (d, ^3J = 2.6 Hz, 2H).

^{13}C NMR ($CDCl_3$): δ = 18.09q, 21.45q, 36.94q, 39.36s, 75.67d, 75.94t, 127.95d, 128.97d, 133.41s, 139.12s.

IR (KBr): ν = 3546 br s, 3025 w, 2981 m, 2840 m, 2882 m, 1487 m, 1473 m, 1343 vs, 1169 vs, 1091 m, 1060 s, 1012 s, 975 s, 957 vs, 866 s, 833 s, 770 m cm^{-1}.

2-(4-Chlorophenyl)-3,3-dimethyloxetane (3d):[32]
^{1}H NMR ($CDCl_3$): δ = 0.78 (s, 3H), 1.39 (s, 3H), 4.24 (d, ^2J = 5.5 Hz, 1H), 4.52 (d, ^2J = 5.5 Hz, 1H), 5.46 (s, 1H), 7.23 (d, ^3J = 8.0 Hz, 2H), 7.31 (d, ^3J = 8.4 Hz, 2H).

^{13}C NMR ($CDCl_3$): δ = 22.37q, 26.79q, 40.04s, 81.21t, 91.04d, 126.45d, 128.27d, 132.13s, 138.71s.

IR (KBr): ν = 3465 w, 2967 m, 2942 m, 1490 m, 1351 vs, 1176 vs, 1089 m, 1009 s, 972 s, 920 s, 812 m cm^{-1}.

Exact mass for $C_{11}H_{13}ClO$ requires: M, 196.065; found: M^+, 196.065.

1-(2-Bromophenyl)-3-methanesulfonyloxy-2,2-dimethyl-1-propanol (2e):
^{1}H NMR ($CDCl_3$): δ = 0.94 (s, 6H), 2.67 (s, 1H), 3.00 (s, 3H), 3.96 (d, ^2J = 9.3 Hz, 1H), 4.36 (d, ^2J = 9.3 Hz, 1H), 5.19 (s, 1H), 7.07–7.54 (m, 4H).

^{13}C NMR ($CDCl_3$): δ = 18.06q, 21.39q, 36.98q, 40.78t, 73.64d, 75.82d, 123.86s, 127.12d, 129.16d, 129.98d, 132.68d, 140.14s.

IR (KBr): ν = 3536 br s, 2973 s, 1467 s, 1353 vs, 1175 vs, 956 br s, 852 s, 830 s, 751 s cm^{-1}.

2-(2-Bromophenyl)-3,3-dimethyloxetane (3e):
^{1}H NMR ($CDCl_3$): δ = 0.84 (s, 3H), 1.61 (s, 3H), 4.30 (d, ^2J = 5.4 Hz, 1H), 4.49 (d, ^2J = 5.4 Hz, 1H), 5.72 (s, 1H), 7.10–7.73 (m, 4H).

^{13}C NMR ($CDCl_3$): δ = 22.12q, 27.30q, 40.33s, 81.30t, 90.52d, 120.72s, 127.29d, 127.76d, 128.55d, 132.14d, 140.04s.

IR (KBr): ν = 3425 br w, 3064 w, 2965 s, 2871 s, 1732 m, 1465 s, 1436 s, 1242 m, 1117 m, 1028 s, 986 vs, 750 s cm^{-1}.

Exact mass for $C_{11}H_{13}BrO$ requires: M, 240.015, found: M^+, 240.015.

3-Methanesulfonyloxy-2,2-dimethyl-1-(4-nitrophenyl)-1-propanol (2f):
^{1}H NMR ($CDCl_3$): δ = 0.87 (s, 3H), 8.89 (s, 3H), 3.06 (s, 3H), 3.16 (s, 1H), 3.88 (d, ^2J = 9.4 Hz, 1H), 4.39 (d, ^2J = 9.4 Hz, 1H), 4.77 (s, 1H), 7.50 (d, ^3J = 8.8 Hz, 2H), 8.15 (d, ^3J = 8.8 Hz, 2H).

^{13}C NMR ($CDCl_3$): δ = 17.90q, 21.59q, 37.03q, 39.54s, 75.16d, 75.65t, 122.84d, 128.59d, 147.30s, 148.35s.

IR (KBr): ν = 3528 br m, 3027 w, 2975 m, 1603 m, 1517 s, 1345 vs, 1172 vs, 1056 m, 957 vs, 856 s, 738 m.

3,3-Dimethyl-2-(4-nitrophenyl)oxetane (3f):
^{1}H NMR ($CDCl_3$): δ = 0.77 (s, 3H), 1.43 (s, 3H), 4.26 (d, ^2J = 5.6 Hz, 1H), 4.55 (d, ^2J = 5.6 Hz, 1H), 5.56 (s, 1H), 7.44 (d, ^3J = 8.2 Hz, 2H), 8.22 (d, ^3J = 8.8 Hz, 2H).

^{13}C NMR ($CDCl_3$): δ = 22.47q, 26.80q, 40.95s, 81.34t, 90.49d, 123.45d, 125.71d, 147.20s, 147.85s.

IR (KBr): ν = 3078 w, 2959 s, 2873 s, 1604 s, 1526 vs, 1462 s, 1343 vs, 1104 s, 1007 s, 985 vs, 868 s, 849 s, 743 s, 701 s cm^{-1}.

Exact mass for $C_{11}H_{10}NO_3$ requires: M, 207.090; found: M^+, 207.090.

3-Methanesulfonyloxy-2,2-dimethyl-1-(2-methoxyphenyl)-1-propanol (2g):
^{1}H NMR ($CDCl_3$): δ = 0.88 (s, 3H), 0.90 (s, 3H), 2.97 (s, 3H), 3.39 (s, 1H), 3.78 (s, 3H), 3.96 (d, ^2J = 9.12 Hz, 1H), 4.27 (d, ^2J = 9.59 Hz, 1H), 4.92 (d, 1H), 6.82–7.39 (m, 4H).

^{13}C NMR ($CDCl_3$): δ = 17,72q, 21.17q, 45.81s, 72.23d, 76.45t, 110.55d, 1120.29d, 128.56d, 129.32d, 156.80s.

IR (KBr): ν = 3534 br s, 3022 w, 2976 s, 1613 m, 1586 m, 1486 s, 1453 s, 1352 vs, 1221 s, 1172 vs, 1048 s, 954 vs, 803 s, 761 s cm^{-1}.

2-(2-Methoxyphenyl)-3,3-dimethyloxetane (3g):
^{1}H NMR ($CDCl_3$): δ = 0.80 (s, 3H), 1.44 (s, 3H), 3.77 (s, 3H), 4.22 (d, ^2J = 5.3 Hz, 1H), 4.51 (d, ^2J = 5.3 Hz, 1H), 5.72 (s, 1H), 6.80–7.56 (m, 4H).

^{13}C NMR ($CDCl_3$): δ = 22.01q, 26.49q, 40.02s, 81.21t, 88.14q, 109.23d, 120.39d, 125.86d, 127.73d, 129.18s, 155.69s.

IR (KBr): ν = 3523 br w, 2965 s, 1694 m, 1599 m, 1489 s, 1463 s, 1353 s, 1240 vs, 1176 s, 1085 s, 1027 s, 1010 s, 972 s, 920 s, 765 s cm^{-1}.

Exact mass for $C_{12}H_{16}O_2$ requires: M, 192.115; found: M^+, 192.115.

3-Methanesulfonyloxy-2,2-dimethyl-1-(4-methoxyphenyl)-1-propanol (2h):
^{1}H NMR ($CDCl_3$): δ = 0.83 (s, 3H), 0.87 (s, 3H), 2.97 (s, 3H), 3.75 (s, 3H), 3.87 (d, ^2J = 9.2 Hz, 1H), 4.26 (d, ^2J = 9.2 Hz, 1H), 4.54 (s, 1H), 6.81 (d, ^3J = 8.7 Hz, 2H), 7.18 (d, ^3J = 8.6 Hz, 2H).

^{13}C NMR ($CDCl_3$): δ = 18.34q, 21.39q, 36.78q, 39.39s, 55.19q, 76.09d, 76.34t, 113.13d, 128.68d, 132.78s, 159.20s.

IR (KBr): ν = 3536 br s, 2970 m, 2937 m, 1609 m, 1513 s, 1464 m, 1351 vs, 1247 s, 1112 vs, 1030 s, 954 vs, 836 s cm^{-1}.

2-(4-Methoxyphenyl)-3,3-dimethyloxetane (3h):[32]
^{1}H NMR ($CDCl_3$): δ = 0.87 (s, 3H), 1.45 (s, 3H), 3.88 (s, 3H), 4.32 (d, ^2J = 5.13 Hz), 1H), 4.58 (d, ^2J = 5.55 Hz, 1H), 5.53 (s, 1H), 6.99 (d, ^3J = 8.6 Hz, 2H), 7.31 (d, ^3J = 9.0 Hz, 2H).

^{13}C NMR ($CDCl_3$): δ = 22.16q, 26.63q, 40.28s, 54.97d, 80.93t, 91.46q, 113.40d, 126.25d, 132.15s, 158.71s.

IR (KBr): ν = 2958 s, 2869 m, 1612 m, 1511 s, 1461 m, 1247 vs, 1169 s, 1034 s, 980 s, 839 m cm^{-1}.

Exact mass for $C_{12}H_{16}O_2$ requires: M, 192.115; found: M^+, 192.115.

1-(2-Ethoxyphenyl)-3-methanesulfonyloxy-2,2-dimethyl-1-propanol (2i):
^{1}H NMR ($CDCl_3$): δ = 0.91 (s, 3H), 0.93 (s, 3H), 1.41 (t, 2H), 2.99 (s, 3H), 3.21 (br, 1H), 3.99 (d, ^2J = 9.3 Hz, 1H), 4.30 (d, ^2J = 9.3 Hz, 1H), 4.92 (d, 1H), 6.82–7.29 (m, 4H).

^{13}C NMR ($CDCl_3$): δ = 14.76q, 18.83q, 21.33q, 36.84q, 40.53s, 63.44t, 73.12d, 76.38t, 111.27d, 120.18d, 128.11s, 128.55d, 129.49d, 156.20s.

IR (KBr): ν = 3541 br m, 3067 w, 2980 m, 2937 m, 1599 m, 1490 m, 1475 m, 1452 m, 1352 vs, 1240 s, 1147 vs, 1044 s, 954 vs, 854 m, 832, 757 m cm^{-1}.

2-(2-Ethoxyphenyl)-3,3-dimethyloxetane (3i):
^{1}H NMR ($CDCl_3$): δ = 0.83 (s, 3H), 1.41 (t, 3H), 1.476 (s, 3H), 4.01 (m, 2H), 4.24 (d, ^2J = 5.2 Hz, 1H), 4.53 (d, ^2J = 5.2 Hz, 1H), 5.76 (s, 1H), 6.79–7.58 (m, 4H).

^{13}C NMR ($CDCl_3$): δ = 14.88q, 22.06q, 26.56q, 39.92s, 63.02t, 81.24t, 88.32d, 109.86d, 120.21d, 125.89d, 127.70d, 129.19s, 155.09s.

IR (KBr): ν = 3069 w, 3041 w, 2963 s, 2928 s, 2869 s, 1600 m, 1490 s, 1476 m, 1453 s, 1283 m, 1245 vs, 1119 s, 1045 s, 984 s, 753 s cm^{-1}.

Exact mass for $C_{12}H_{18}O_2$ requires: M, 206.131; found: M^+, 206.131.

1-Isopropyl-3-methanesulfonyloxy-2,2-dimethyl-1-propanol (2j):
^{1}H NMR ($CDCl_3$): δ = 0.90–1.00 (q, 12H), 1.96 (m, 2H), 3.00 (s, 3H), 3.33 (d, 1H), 3.84 (d, ^2J = 9.2 Hz, 1H), 4.22 (d, ^2J = 9.2 Hz, 1H).

^{13}C NMR ($CDCl_3$): $\delta = 16.84$q, 18.97q, 21.93q, 23.32q, 28.56d, 36.88q, 39.54s, 76.82t, 77.81d.

IR (KBr): $\nu = 3551$ br, s, 3016m, 2967s, 1469m, 1341vs, 1169vs, 981s, 969s, 950vs, 858m, 749m cm^{-1}.

2-Isopropyl-3,3-dimethyloxetane (3j):[36]
^{1}H NMR ($CDCl_3$): $\delta = 0.70$ (d, $^3J = 6.51$ Hz, 3H), 0.84 (d, $^3J = 6.51$ Hz, 3H), 1.15 (d, 3H), 1.20 (d, 3H), 1.94 (m, 1H), 3.88 (d, $^2J = 10.5$ Hz, 1H), 3.9 (d, $^2J = 5.2$ Hz, 1H), 4.24 (d, $^2J = 5.27$ Hz, 1H).

^{13}C NMR ($CDCl_3$): $\delta = 17.04$q, 17.77q, 20.82q, 20.82q, 26.66q, 30.05d, 38.30t, 79.81s, 95.87d.

IR (KBr): $\nu = 3431$ brw, 2956vs, 2928vs, 2872vs, 1732w, 1699w, 1469s, 1388m, 1370m, 1034m, 982s, 936m, 854w cm^{-1}.

Exact mass for $C_8H_{16}O$ requires: M, 128.120; found: M^+, 128.120.

3-Methanesulfonyloxy-2,2-dimethyl-1-(2-thienyl)-1-propanol (2k):
^{1}H NMR ($CDCl_3$): $\delta = 0.93$ (s, 3H), 0.99 (s, 3H), 2.98 (s, 3H), 3.91 (d, $^2J = 9.2$ Hz, 1H), 4.26 (d, $^2J = 9.2$ Hz, 1H), 4.88 (d, 2H), 6.92–7.27 (m, 3H).

^{13}C NMR ($CDCl_3$): $\delta = 18.59$q, 21.27q, 36.82q, 39.35s, 73.16d, 75.97t, 124.71d, 125.64d, 126.35d, 144.32s.

IR (KBr): $\nu = 3529$ br m, 3072w, 2938m, 1472m, 1349vs, 1174vs, 956vs, 843s, 709s cm^{-1}.

3,3-Dimethyl-2-(2-thienyl)oxetane (3k):
^{1}H NMR ($CDCl_3$): $\delta = 0.98$ (s, 3H), 1.38 (s, 3H), 4.32 (d, $^2J = 5.5$ Hz, 1H), 4.47 (d, $^2J = 5.5$ Hz, 1H), 5.66 (s, 1H), 6.94–7.31 (m, 3H).

^{13}C NMR ($CDCl_3$): $\delta = 22.15$q, 26.52q, 41.09s, 81.28d, 88.75d, 123.51d, 124.62d, 126.83d, 143.82s.

IR (KBr): $\nu = 3483$ brw, 3104w, 3071w, 2969s, 2933s, 1721m, 1669m, 1472s, 1361s, 1090vs, 1041s, 856m, 833m, 696s cm^{-1}.

Exact mass for $C_9H_{12}SO$ requires: M, 168.061; found: M^+, 168.061.

α-(1-Methanesulfonyloxymethyl-1-cyclohexyl)benzyl Alcohol (2l):
^{1}H NMR ($CDCl_3$): $\delta = 1.05$–1.57 (m, 10H), 2.97 (s, 3H), 4.16 (d, $^2J = 9.6$ Hz, 1H), 4.39 (d, $^2J = 9.6$ Hz, 1H), 4.66 (s, 1H), 7.25–7.39 (m, 5H).

^{13}C NMR ($CDCl_3$): $\delta = 21.04$t, 21.23t, 25.64t, 26.94t, 27.61t, 36.84q, 41.32s, 70.58t, 76.45d, 127.57d, 127.70d, 127.92d, 140.58.

IR (KBr): $\nu = 3541$ brs, 3029m, 2934vs, 2865s, 1722w, 1669w, 1601w, 1452s, 1348vs, 1171vs, 1041s, 950vs, 838s, 705s.

1-Phenyloxaspiro[3,5]nonane (3l):[37]
^{1}H NMR ($CDCl_3$): $\delta = 0.89$–2.14 (m, 10H), 4.38 (d, $^2J = 5.6$ Hz, 1H), 4.55 (d, $^2J = 5.6$ Hz, 1H), 5.46 (s, 1H), 7.26–7.44 (m, 5H).

^{13}C NMR ($CDCl_3$): $\delta = 22.04$t, 23.29t, 25.48t, 31.78t, 37.11t, 44.40s, 79.77s, 91.85d, 125.67d, 127.25d, 127.92d, 139.98s.

IR (KBr): $\nu = 3402$ brw, 3061w, 3026w, 2931vs, 2854vs, 1720s, 1448s, 1271s, 1114m, 983m, 700s cm^{-1}.

Exact mass for $C_{14}H_{18}O$ requires: M, 202.136; found: M^+, 202.136.

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(34) (a) All of the oxetanes have TLC R_f values of 0.90–0.97 on plates of aluminium oxide using Et_2O as eluant.
(b) 3,3-Dimethyl-2-(2-thienyl)oxetane **(3k)** was isolated by distillation without chromatographic purification; this compound spontaneously forms a viscous polymer in a few days.
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