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Efficient Oxidation of 1,2-Diols into α-Hydroxyketones Catalyzed by Organotin Compounds

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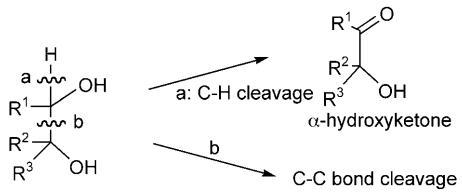
Abstract: Electrochemical oxidation of 1,2-diols with a catalytic amount of an organotin compound and a bromide ion as mediators has been developed. Various cyclic and acyclic 1,2-diols were oxidized into the corresponding α-hydroxyketones in good to excellent yields without C–C bond cleavage. Also, oxidation with the use of chemical oxidants was accomplished in the presence of a catalytic amount of an organotin compound. These reactions could discriminate 1,2-diols from isolated hydoxyl groups or 1,3-diols. In the case of a conformationally restricted cyclic 1,2-diol, the axial hydroxyl group was oxidized exclusively. Mono-, di-, and trialkylated tin compounds were examined as mediators and dialkylated tin compounds showed higher catalytic activity than mono- and trisubstituted ones. Me_2SnCl_2 was found to be the most suitable mediator for the selective oxidation.

Keywords: chemoselectivity · diols · ketones · organotin catalysts · oxidation

Introduction

Oxidation of alcohols into their corresponding ketones is one of the most basic organic reactions. However, most common oxidizing reagents or methods, such as $Pb(OAc)_4$,[1] IO_4^-,[2] Cr^{IV},[3] Ce^{IV}[4] and electrochemical oxidation[5] cause the oxidative C–C bond cleavage of 1,2-diols (path b in Scheme 1). Few methods are available for the selective oxidation of 1,2-diols into α-hydroxyketones (path a in Scheme 1) in spite of their usefulness as intermediates for organic synthesis.[6]

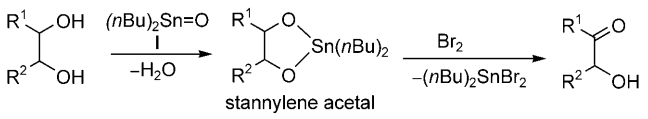


Scheme 1. Oxidation of 1,2-diols.

Some of the methods involve the use of silver carbonate on Celite (Fetizon reagent),[7] the Corey–Kim reagent,[8] peroxotungstophosphate with H_2O_2,[9] the Swern reagent,[10] *N*-bromosuccinimide (NBS),[11] or $nBu_2Sn{=}O$ (**I**).[12] These reagents with the exception of **I** suffer from disadvantages, such as relatively low yields, side reactions accompanying C–C bond cleavage especially for the oxidation of cyclic 1,2-diols,[9] and over-oxidation to 1,2-diketones.[10]

On the other hand, the use of **I** has been recognized as a highly selective method,[12] which proceeds in two stages: formation of stannylene acetals by azeotropic condensation of 1,2-diols with **I** followed by the oxidation of the stannylene acetals with bromine (Scheme 2).

Since the method does not need any protection–deprotection procedures, it has been applied to the synthesis of (+)-spectinomycin[13] and to the oxidation of a variety of sugars into oxo-sugars.[12c] This method, however, requires more than an equimolar amount of **I** to complete the oxidation. It is troublesome and also unfavorable from an environmental



Scheme 2. Oxidation of 1,2-diols via a stannylene acetal.

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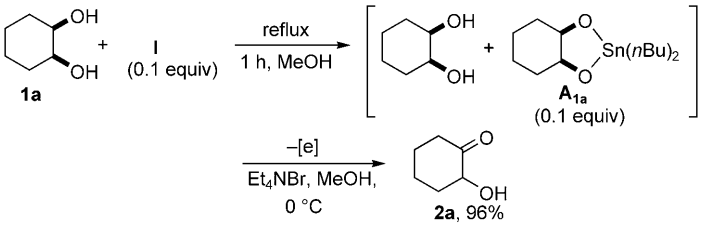
viewpoint. Previously, we reported an electrochemical method for the effective oxidation of 1,2-diols in which both **I** and a bromide ion worked as mediators to oxidize 1,2-diols, and therefore only a catalytic amount (0.02 to 0.1 equiv) of **I** was enough to complete the oxidation.[14] In our continuing study on this method, we examined a variety of organotin compounds[15] and found a number of them could work as more efficient mediators than **I**.[16] We report herein the details of our results.

Results and Discussion

Catalytic activity of various organotin mediators for the oxidation of 1,2-diols: Electrochemical oxidation of *cis*-1,2-cyclohexanediol (**1a**) in methanol containing 0.1 equivalents of **I** and Et_4NBr at room temperature gave α-hydroxycyclohexanone (**2a**) in 96% yield. This oxidation required preheating of the solution prior to electrolysis to dissolve **I**. Since it is well-known that heating of **I** in methanol containing **1a** gives stannylene acetal ($\mathbf{A_{1a}}$) and as an electrochemical oxidation of **1a** without **I** did not proceed, this means that $\mathbf{A_{1a}}$ would be oxidized by Br^+, which was generated by electrochemical oxidation of Br^- (Scheme 3).



Scheme 3. Electrochemical oxidation of **1a** by using **I** and Br^-.

To explore the catalytic activity of organotin compounds, we examined various organotin compounds **I**–**X** for the oxidation of **1a** and 1,2-dodecanediol (**1b**). Table 1 shows the results.

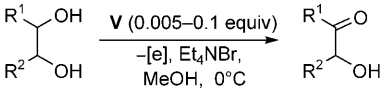
For the oxidation of **1a**, preheating was required to dissolve dialkyltin oxide **I** or **II** in methanol, whereas for the oxidation of **1b** by using **I** or **II**, preheating was an inhibitor (Table 1, entries 1–4). Dialkylated and trialkylated tin compounds **III**–**VIII** showed moderate to excellent catalytic activity without preheating for the oxidation of cyclic diol **1a** (entries 5–10). On the other hand, oxidation of acyclic diol **1b** to **2b** was not satisfactorily achieved by nOct$_2$Sn=O (**II**), nBu$_2$SnCl$_2$ (**III**), or nBu$_3$SnCl (**VIII**) (entries 4, 5, and 10), whereas nBu$_2$SnBr$_2$ (**IV**), Me$_2$SnCl$_2$ (**V**), tBu$_2$SnCl$_2$ (**VI**), and Ph$_2$SnCl$_2$ (**VII**) mediated the oxidation with moderate efficiency (entries 6–9). Although (nBu$_3$Sn)$_2$O (**IX**) worked well for the oxidation of both **1a** and **1b** (entry 11), nBuSnCl$_3$ (**X**) was effective only for the oxidation of **1a** (entry 12). Thus, some organotin compounds showed catalytic activity for the oxidation of 1,2-diols by an electrochemical method. Among them, **V** looks promising as a catalyst for the oxidation because of its applicability to both cyclic and acyclic diols. Furthermore, **V** showed good solubility toward methanol, and thus the procedure did not require heating at reflux of the solution before the experiment, which was essential in the case of **II**.[15] The procedure using **V** is therefore a one-step procedure.

Table 1. Electrochemical oxidation of **1a** and **1b** by using organotin compounds.

Entry	Organotin compound (0.1 equiv)		Yield [%] of α-hydroxyketone	
			2a[a] (2 Fmol^{-1})	**2b**[b] (3 Fmol^{-1})
1	nBu$_2$Sn=O	**I**	6	43
2[c]	nBu$_2$Sn=O	**I**	96	–[d]
3	nOct$_2$Sn=O	**II**	40	10
4[c]	nOct$_2$Sn=O	**II**	95	–[d]
5	nBu$_2$SnCl$_2$	**III**	79	–[d]
6	nBu$_2$SnBr$_2$	**IV**	71	77
7	Me$_2$SnCl$_2$	**V**	70	82
8	tBu$_2$SnCl$_2$	**VI**	89	76
9	Ph$_2$SnCl$_2$	**VII**	63	82
10	n-Bu$_3$SnCl	**VIII**	59	–[d]
11	(nBu$_3$Sn)$_2$O	**IX**	77	66
12	nBuSnCl$_3$	**X**	57	11

[a] Determined by GC analysis. [b] Isolated yield. [c] The reaction solution was heated at reflux for 1 h prior to the electrolysis. [d] Many unidentified products formed with the product.

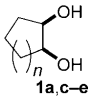
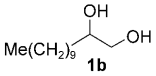
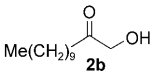
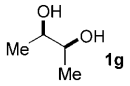
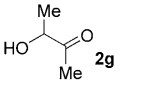
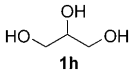
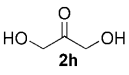
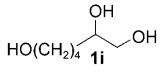
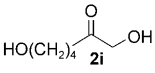
Electrochemical oxidation of various 1,2-diols by using V: According to the procedure, a variety of 1,2-diols were oxidized into α-hydroxyketones by the electrochemical method by using **V** as a mediator [Eq. (1)]. The electrolysis was carried out in the presence of 0.005 to 0.1 equivalents of **V** at 0°C in methanol. During the electrolysis, a yellowish/green solution was observed on the surface of the anode. The results are summarized in Table 2.



(1)

Cyclic *cis*-1,2-diols were selectively oxidized to α-hydroxyl ketones **2** in good yields irrespective of their ring size and without C–C bond cleavage (Table 2, entries 1–4). The yield of **2a** from *trans*-1,2-cyclohexanediol (**1f**) was relatively lower than that from *cis*-isomer **1a**, because oxidation of **1f** proceeds more slowly than that of **1a** as previously reported[14] (entries 1 and 5). This relatively small reaction rate may be due to the fact that both of the hydroxyl groups are located in an equatorial position in **1f** and need to pass through a high-energy transition state (see section on stereoselectivity). However, the yield of **2a** from **1f** was improved when the electrolysis was carried out at a lower current density in a mixed solvent system of dichloromethane and trifluoroethanol in a ratio of 10:1, which are less oxidizable solvents than methanol (entry 6). A larger amount of electricity was necessary to complete the oxidation of acyclic diols than cyclic diols. The secondary hydroxyl group in acy-

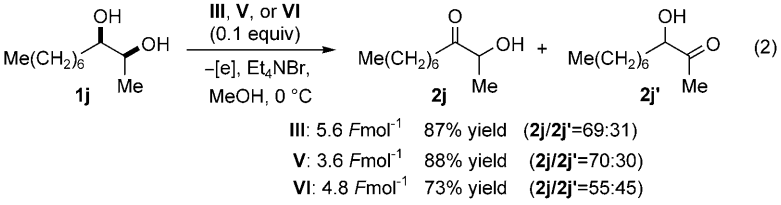
Table 2. Electrochemical oxidation of 1,2-diols mediated by **V** and Br^-.

Entry	1,2-Diol		**V** [equiv]	Electricity [Fmol^{-1}]	Product	Yield [%][a]
1	 **1a**,**c**–**e**	**a**: $n=2$	0.1	3.0	 **2a**,**c**–**e**	89[b]
2		**c**: $n=1$	0.1	3.0		70[b]
3		**d**: $n=3$	0.1	3.0		84
4		**e**: $n=4$	0.1	3.0		87
5	 **1f**		0.1	3.0		41
6[c]			0.1	2.0	**2a**	74
7	 **1b**		0.1	3.0	 **2b**	76
8			0.005	4.6		72
9	 **1g**		0.1	3.0	 **2g**	56[d]
10	 **1h**		0.1	3.0	 **2h**	32[d]
11	 **1i**		0.1	4.0	 **2i**	76

[a] Isolated yield unless otherwise noted. [b] Determined by GC analysis. [c] Solvent: CH_2Cl_2/CF_3CH_2OH 10:1. [d] Isolated yield after benzoylation.

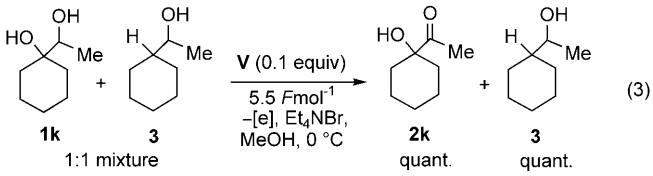
clic 1,2-diols was selectively oxidized into a carbonyl group in a moderate to good yield (entries 7–11). Although the current efficiency was decreased, only 0.005 equivalents of **V** was required for efficient reaction (entry 8).

Regioselectivity: Oxidation of a 1,2-diol, which is composed of two secondary hydroxyl groups, such as **1j** afforded a mixture of two regioisomers of α-hydroxyketones **2j** and **2j′**. That is, when using nBu$_2$SnCl$_2$ (**III**) or Me$_2$SnCl$_2$ (**V**), the more hindered hydroxyl group was oxidized predominantly in a ratio of 70 to 30, whereas the ratio decreased from 55 to 45 when using tBu$_2$SnCl$_2$ (**VI**) as an organotin catalyst [Eq. (2)].



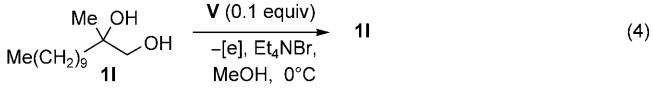
(2)

Chemoselectivity: The reaction showed a high selectivity for 1,2-diols. For example, a mixture of an equimolar amount of secondary/tertiary diol **1k** and secondary alcohol **3** was subjected to the electrolysis. After passing 5.5 Fmol^{-1} of electricity, **2k** was obtained quantitatively, whereas **3** remained unchanged [Eq. (3)].



(3)

Primary/tertiary vicinal diols, such as **1l** could not be oxidized by this reaction [Eq. (4)]. These results indicate that the oxidization of the primary hydroxyl group does not take place in this reaction. Moreover, the result shows that tertiary and primary hydroxyl groups can act as an anchor for the organotin catalyst to activate only their vicinal secondary hydroxyl groups for the selective oxidation. 1,3-Butanediol (**4**) was also inert under the same conditions [Eq. 5)]. Thus, from these results we deduced that secondary alcohols in 1,2-diols are selectively oxidized by this reaction. This tendency is contrastive with the fact that organotin-catalyzed monobenzoylation predominantly takes place at the primary hydroxyl group of acyclic secondary/primary diols.[15]



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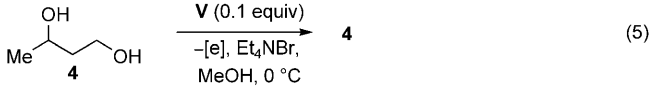
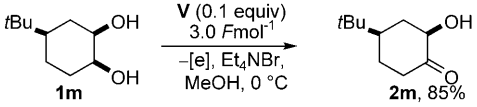


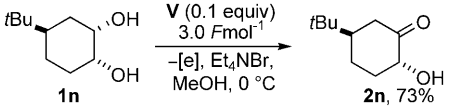
(5)

Stereoselectivity: The current efficiency and chemical yield of α-hydroxyketone **2** were strongly affected by the structure of the 1,2-diols (Table 2, entries 1 and 5). This result prompted us to investigate the stereoselectivity of this reaction. Conformationally restricted cyclic 1,2-diols, such as **1m** and **1n**, were prepared. After the electrochemical oxidation of **1m** and **1n** in the presence of **V** and Br^-, it was found that their axial hydroxyl groups had been selectively oxidized into carbonyl groups, such as **2m** and **2n**, respectively, as a single isomer [Eqs. (6) and (7)].

This finding is in line with the result of the brominolysis of stannylene acetals derived from sugars and **I** reported by Tsuda et al.[12c] This could also account for the relatively lower yield of **2a** from **1f** than that from **1a** (Table 2, entries 1 and 5). In **1a**, one of the hydroxyl groups occupies an



(6)



(7)

axial position that might be easily oxidized; this is not the case in **1f**.

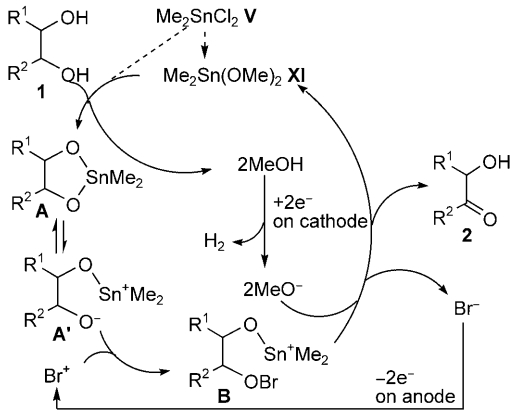
Oxidation potentials: Oxidation peak potentials of materials used in these oxidations were measured by cyclic voltammetry. The results are shown in Table 3. The most oxidizable species was Br^-, whereas Me_2SnCl_2 (**V**) was hardly oxidized (entries 1 and 2). The intriguing point is that the oxidation potential of 1,2-*cis*-cyclooctanediol (**1e**) shifted by −90 mV in the presence of **V** (entries 3 and 4). On the other hand, such a negative shift was not observed in the oxidation potential of α-hydroxyketone **2e** (entries 5 and 6).

Table 3. Oxidation peak potentials observed by cyclic voltammetry.

Entry	Substrates	Oxidation potential [V][a]
1	Et_4NBr	1.15
2	Me_2SnCl_2 (**V**)	>3.0
3	diol **1e**	2.13
4	mixture of **1e**/**V**	2.04
5	α-hydroxyketone **2e**	2.59
6	mixture of **2e**/**V**	2.59

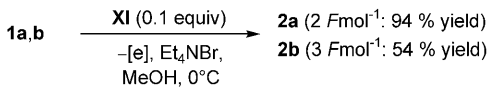
[a] Cyclic voltammograms were recorded on each substrate solution (10 mM) in MeCN containing Et_4NBF_4 (0.1 M): Glassy carbon disk working electrode (1.6 mm); scan rate: 0.1 V s^{-1}; Ag/$AgNO_3$ as reference.

Reaction mechanism for electrochemical oxidation: A plausible reaction mechanism for the electrochemical oxidation of 1,2-diols **1** is shown in Scheme 4. Dimethylstannylene acetal or related complex **A** or **A′** could be oxidized with a combination of anodically generated oxidant (Br^+) and cathodically generated base ($2MeO^-$) to afford α-hydroxyketones **2** and to regenerate $Me_2Sn(OMe)_2$ (**XI**). In this electrochemical method, it is important that both the oxidant and the base are generated with an accurate molar ratio so that the acidity of the whole system does not change in the course of the reaction.



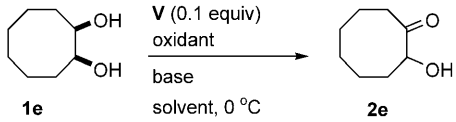
Scheme 4. Reaction mechanism for the electrochemical oxidation of 1,2-diols.

To further confirm the viability of this mechanism, **XI**, prepared by the reported method,[17] smoothly supported the electrochemical oxidation of **1a**,**b** into **2a**,**b** [Eq. (8)]. Thus, in place of the electrochemical method, chemical methods including a combination of heterogeneous base and oxidant were constructed for this catalytic system.



(8)

Chemical oxidation: Based on the speculated mechanism, a similar chemical process has been examined. The oxidation of *cis*-1,2-cyclooctanediol (**1e**) into 2-hydroxycyclooctanone (**2e**) was carried out by using **V** (0.1 equiv) with a variety of chemical oxidants and solvents at 0 °C [Eq. (9)]. The results are summarized in Table 4.



(9)

Bromine (Br_2) worked well as an oxidant for **1e** in methanol in the presence of K_2CO_3 as a heterogeneous base (Table 4, entries 1 and 2), whereas iodine was not effective

Table 4. Chemical oxidation of **1e** by using a halogen cation species.

Entry	Oxidant ([equiv])	Solvent	Base ([equiv])	Reaction *t*	Yield [%][a] of **2e**
1	Br_2 (1.2)	MeOH	K_2CO_3 (3.0)	30 min	71
2	Br_2 (2.0)	MeOH	K_2CO_3 (3.0)	30 min	79
3	Br_2 (2.0)	MeOH	–	30 min	24
4	I_2 (1.2)	MeOH	K_2CO_3 (3.0)	3 h	4
5	NCS (1.2)	MeOH	–	3 h	trace
6	NBS (1.2)	MeOH	–	3 h	37
7	NIS (1.2)	MeOH	–	3 h	24
8	Br_2 (1.2)	CH_2Cl_2	K_2CO_3 (3.0)	30 min	38
9	NBS (1.2)	CH_2Cl_2	–	3 h	21
10	NBS (2.0)	CH_2Cl_2	–	3 h	27
11	NIS (1.2)	CH_2Cl_2	-	3 h	54
12	NIS (2.0)	CH_2Cl_2	–	3 h	82
13	NIS (2.0)	CH_2Cl_2	K_2CO_3 (3.0)	3 h	83
14	Br_2 (1.2)	AcOEt	K_2CO_3 (3.0)	30 min	64
15	NIS (2.0)	AcOEt	–	3 h	73
16	Br_2 (1.2)	MeCN	K_2CO_3 (3.0)	30 min	52
17	NIS (2.0)	MeCN	–	3 h	70

[a] Isolated yield.

(entry 4). The absence of K_2CO_3 led to a low yield (entry 3). The use of dichloromethane, ethyl acetate, or acetonitrile as the solvent in combination with Br_2 as the oxidant afforded a lower yield of **2e** compared to when methanol was used (entries 8, 14 and 16). NBS and *N*-iodosuccinimide (NIS) oxidized **1e** albeit in low yields in the absence of K_2CO_3 in methanol (entries 6 and 7), whereas *N*-chlorosuccinimide (NCS) hardly oxidized **1e** (entry 5). In the case of NIS, the yields of **2e** improved when using other solvents, such as dichloromethane, ethyl acetate, or acetonitrile (entries 11, 15, and 17). The use of 2.0 equivalents of NIS in dichloromethane gave optimal reaction conditions. Addition of K_2CO_3 did not affect the yield of **2e** (entries 12 and 13).

Although the yield of **2e** was slightly lower than that obtained when using the electrochemical method (87% yield, Table 2, entry 4), this procedure was very convenient.

Next, the chemical oxidation of various 1,2-diols **1a–e** by using **V** was examined under the two optimized reaction conditions: 1) method A: 2.0 equivalents of Br_2, 0.1 equivalents of **V**, and 3.0 equivalents of K_2CO_3 in methanol and 2) method B: 2.0 equivalents of NIS and 0.1 equivalenst of **V** in dichloromethane [Eq. (10)]. The results are summarized in Table 5.

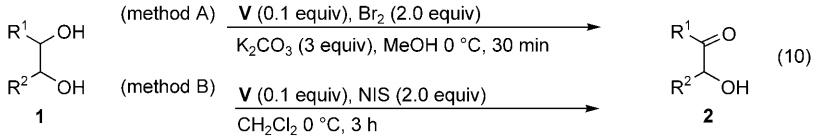


Table 5. Chemical oxidation of 1,2-diols mediated by **V**.

Entry	1,2-Diol	Product	Yield [%][a] of **2**	
			Method A	Method B
1	**1a**	**2a**	82[b,c]	84[c]
2	**1b**	**2b**	86	26
3	**1c**	**2c**	94[c]	54[c]
4	**1d**	**2d**	74	73
5	**1e**	**2e**	79	82
6[d]	**1e**	**2e**	75	72
7	**1f**	**2a**	91[c]	81[c]
8	**1i**	**2i**	62	57

[a] Isolated yield unless otherwise noted. [b] 1.2 equivalents of Br_2 was used. [c] Determined by GC analysis. [d] **XI** was used instead of **V**.

Method A was applicable to the oxidation of **1a–f,i** to afford **2a–e,i** in good to high yields. On the other hand, method B was applicable to the effective oxidation of **1a,c–f,i**, but it was not effective for the oxidation of 1,2-dodecanediol **1b**. Moreover, catalyst **XI** could also be used for the oxidation (Table 5, entry 6).

Conclusion

We have presented an organotin-catalyzed oxidation of 1,2-diols into α-hydoxyketone by means of an electrochemical procedure in which the oxidation proceeded under neutral conditions at 0°C in methanol with interesting selectivity. Also, the corresponding chemical oxidation with Br_2 or NIS was exploited for a convenient oxidation method. Since the presented catalytic reaction proceeds by the selective activation of diols, the tolerance level of the oxidation technique to coexisting functional groups could be controlled by the proper choice of these chemical oxidants. The presented procedure showed the following characteristics: 1) cyclic 1,2-diols of various ring sizes could be oxidized into α-hydroxyketones; 2) the reaction discriminated between 1,2-diols and isolated hydroxyl groups or 1,3-diols; 3) The axial hydroxyl group was oxidized exclusively if the ring conformation was restricted (this information is useful for the prediction of results for the oxidation of cyclic diols); 4) dialkylated tin dihalide compounds have good catalytic activity for the oxidation and this made the procedure absolutely one step. Dimethyltin dichloride **V** was singled out as a suitable catalyst because of its solubility in organic solvents and good catalytic activity for oxidation of both the cyclic- and acyclic 1,2-diols. This result avails the possibility to design new catalysts for other selective oxidations.

Experimental Section

General: Electrochemical reactions were carried out by using a DC Power Supply (GP 050–2) from Takasago Seisakusho, Inc. HPLC analyses were achieved by using a LC-10AT *VP* and a SPD-10A *VP* of Shimadzu Seisakusho, Inc. ^{1}H and ^{13}CNMR spectra were measured at 300 and 75 MHz on a Varian Gemini 300 spectrometer or on a Varian UNITY-plus 500 MHz NMR spectrometer with TMS as an the internal standard. All melting points were measured on MICRO MELTING POINT APPARATUS (Yanaco) and are uncorrected. IR spectra were obtained on a Shimadzu FTIR-8100A. Mass spectra were obtained on a JEOL JMS-DX 303 instrument.

All reagents and solvents were used as supplied without further purification. Organotin catalysts **I–X**, diols **1a–c**, **1e–g**, and **4**, monol **3**, and triols **1h,i** were commercially available. Diols **1d**,[18] **1j**,[19] and **1k**[20] were prepared by osmium oxidation of cycloheptene, *cis*-2-decene, and ethylidenecyclohexane, respectively. Diol **1l**[21] was synthesized by the reaction of **2b**[22] with a large excess of methylmagnesium iodide. α-Hydroxyketones **2a**,[23] **2c**,[23] **2d**,[24] **2e**,[24] **2g**[24] (its *O*-benzoylated derivative[25]), 1,3-dibenzoyloxyacetone[26] derived from **2h**, **2i**,[27] **2j**,[28] **2j′**,[29] and **2k**[29] are known compounds.

Preparation of 1,2-diols

4-*tert*-Butyl-1,2-cyclohexanediol (1m,n): A solution of 4-*tert*-butylcyclohexanol (15.6 g, 100 mmol) in dimethylsulfoxide (20 mL) in a flask equipped with a reflux condenser was heated up to 180°C in an oil bath. After 24 h, distillation afforded crude 4-*tert*-butylcyclohexene (6.2 g) as an oil. A solution of *N*-methylmorpholine-*N*-oxide (17.6 g, 150 mmol) in acetonitrile (30 mL) containing water (5 mL) was carefully degassed by nitrogen bubbling. The crude 4-*tert*-butylcyclohexene and aqueous OsO_4 (3% w/v, 3 mL) were added to the degassed solution and stirred for 17 h at ambient temperature. After the usual workup, diols **1m** and **1n** were obtained as an 1:1 mixture (determined by the integral intensity of ^{1}H NMR spectra); 33% from starting 4-*tert*-butylcyclohexanol. The mixture of **1m** and **1n** was treated with benzoylchloride in the presence of 4-dimethylaminopyridine in dichloromethane (50 mL) to give a mixture of diastereomers **4m** and **4n** in 98% yield. The mixture was separable by

silica-gel column chromatography (*n*-hexane/AcOEt 20:1, polar isomer: **4m**, less polar isomer: **4n**). The stereochemistry of these isomers was confirmed by observation of a NOE effect between ^{1}H NMR spectroscopic signals of axial protons at C2, C4, and C6 in **4m**, and at C1, C3, and C5 in **4n** (Figure 1).

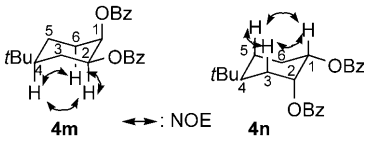


Figure 1. NOE experiment of **4m** and **4n**.

1,2,4-cis-*Dibenzoate (**4m**)*: White solid; m.p. 90–92 °C; ^{1}H NMR ($CDCl_3$): δ = 0.96 (s, 9H), 2.34–2.49 (m, 2H), 2.64–2.73 (m, 2H), 2.81 (q, J = 10.1 Hz, 1H), 2.01–2.07 (m, 1H), 2.18–2.24 (m, 1H) 5.18 (ddd, J = 2.7, 4.7, 11.8 Hz, 1H), 5.61 (brs, 1H), 7.29–7.34 (m, 2H), 7.44–7.50 (m, 3H), 7.56–7.60 (m, 1H), 7.89–7.93 (m, 2H), 8.03–8.12 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ = 20.5, 27.4, 27.6, 28.9, 32.4, 45.9, 69.7, 73.9, 128.1, 128.4, 129.4, 129.5, 130.2, 130.6, 132.7, 132.8, 165.55, 165.61 ppm; IR: $\tilde{\nu}$ = 2961, 2870, 1721, 1451, 1316, 1175, 1098, 710 cm^{-1}; HR-EI: *m*/*z*: calcd for $C_{24}H_{28}O_4$: 380.1988 $[M]^+$; found: 380.1988.

1,2-cis-*1,4*-trans-*Dibenzoate (**4n**)*: White solid; m.p. 95–98 °C; ^{1}H NMR ($CDCl_3$): δ = 0.89 (s, 9H), 1.23–1.36 (m, 1H), 1.48–1.60 (m, 2H), 1.95–2.08 (m, 3H), 2.17–2.21 (m, 1H), 5.09–5.12 (m, 1H), 5.71 (brs, 1H), 7.29–7.31 (m, 2H), 7.43–7.52 (m, 3H), 7.58–7.61 (m, 1H), 7.89–7.93 (m, 2H), 8.07–8.15 ppm (m, 2H); ^{13}C NMR ($CDCl_3$): δ = 25.0, 26.6, 27.5, 30.6, 32.0, 41.0, 70.8, 73.5, 128.2, 128.4, 129.5, 129.6, 130.2, 130.7, 132.8, 132.9, 165.76, 165.82 ppm; IR: $\tilde{\nu}$ = 2957, 2870, 1719, 1281, 1451, 1366, 1117, 1096, 712 cm^{-1}; HR-EI: *m*/*z*: calcd for $C_{24}H_{28}O_4$: 380.1988 $[M]^+$; found: 380.1995.

Alkaline hydrolysis of **4m** and **4n** afforded pure **1m** and **1n**, respectively, as single isomers in quantitative yields.

1,2-cis-*1,4*-cis-*isomer (**1m**)*: White solid; m.p. 104–105 °C; ^{1}H NMR ($CDCl_3$): δ = 0.88 (s, 9H), 0.99–1.06 (m, 1H), 1.12–1.49 (m, 4H), 1.72 (brd, 1H), 1.90–2.01 (m, 1H), 2.25 (brs, 1H), 3.55–3.65 (m, 1H), 3.94 ppm (brs, 1H); IR: ν = 3373, 2970, 2003, 1437, 1238, 1069, 1001 cm^{-1}; HR-EI: *m*/*z*: calcd for $C_{10}H_{20}O_2$: 172.1463 $[M]^+$; found: 172.1463.

1,2-cis-*1,4*-trans-*isomer (**1n**)*: White solid; m.p. 78–79 °C; ^{1}H NMR ($CDCl_3$): δ = 0.84–0.88 (m, 9H), 0.92–1.82 (m, 6H), 1.90–2.05 (m, 1H), 2.50 (brs, 1H), 3.47–3.63 (m, 1H), 4.02 ppm (brd, 1H);IR: $\tilde{\nu}$ = 3390, 2950, 2870, 1366, 1071, 988, 902, 828 cm^{-1}; HR-EI: *m*/*z*: calcd for $C_{10}H_{20}O_2$: 172.1463 $[M]^+$; found: 172.1466.

Measurement of oxidation potentials: BAS CV-50W was used as a voltametric analyzer. A solution of substrate (0.1 mmol) in MeCN (10 mL) containing 0.1 M Et_4NBF_4 was measured. The reference electrode was Ag/$AgNO_3$ in saturated aqueous KCl, whereas glassy carbon was the working electrode, and platinum wire was the counter electrode. The scan rate was 100 mV s^{-1}.

Electrochemical oxidation of 1,2-diols 1a or 1b by using I or II under preheating conditions: **General procedure**: A solution of 1,2-diol **1a** or **1b** (1.0 mmol) and tin oxide **I** (0.1 mmol) in methanol (5 mL) was heated at reflux for 1 h before electrolysis. The resulting solution was transferred into a glass cell equipped with a platinum anode and cathode (1 × 2 cm). Et_4NBr (1.0 mmol) was added to the solution as a supporting electrolyte and also mediator. Then, the mixture was subjected to constant current electrolysis (100 mA) at 0 °C until **1a** or **1b** disappeared, as determined by TLC.

*Oxidation of **1a***: A solution of *n*-dodecane (1 mmol) in CH_2Cl_2 was added to the resulting reaction mixture. The yield of **2a** was determined by GLC.

GLC conditions: DB-1 (J&W SCIENTIFIC) 30 m × 0.25 mmφ; *P*: 100 kP; *T*: initial: 80 °C (5 min), then the temperature rose by 5 °C min^{-1}, retention time: 5.9 (**2a**), 3.9 (**2c**), 13.5 min (*n*-dodecane).

*Oxidation of **1b***: Aqueous sat. NaCl (10 mL) was added to the resulting reaction mixture. The organic portion was extracted with AcOEt (3 × 40 mL). After the organic layer had been dried over $MgSO_4$, the solvent was removed in vacuo. The residue was subjected to silica-gel column chromatography (*n*-hexane/AcOEt 10:1) to afford **2b**.

Electrochemical oxidation of 1,2-diols by using I–XI: **General procedure**: A solution of 1,2-diol **1a** (1.0 mmol) and tin catalyst **V** (0.1 mmol) in methanol (5 mL) was poured into a glass cell equipped with a platinum anode and cathode (1 cm × 2 cm). Et_4NBr (1.0 mmol) was added to the solution as a supporting electrolyte and also mediator. Then the mixture was subjected to constant current electrolysis (100 mA) at 0 °C until **1a** disappeared on TLC.

cis-*3*-tert-*Butyl-2-hydroxycyclohexanone (**2m**)*: White solid; m.p. 64–67 °C; ^{1}H NMR ($CDCl_3$): δ = 0.86–0.96 (m, 9H), 1.32 (q, J = 12.5 Hz, 1H), 1.44 (dq, J = 4.2, 12.9 Hz, 1H), 1.65 (tt, J = 3.0, 12.7 Hz, 1H), 2.12 (m, 1H), 2.38 (m, 1H), 2.47 (m, 1H), 2.56 (m, 1H), 3.32 (m, 1H), 4.16 ppm (m, 1H); ^{13}C NMR ($CDCl_3$): δ = 27.55, 28.4, 32.3, 35.8, 38.3, 45.1, 74.8, 211.6 ppm; IR: $\tilde{\nu}$ = 3488, 2967, 2870, 1727, 1678, 1397, 1368, 1109, 1090, 872 cm^{-1}; HR-EI: calcd for $C_{10}H_{18}O_2$: 170.1307 $[M]^+$; found: 170.1307.

trans-*5*-tert-*Butyl-2-hydroxycyclohexanone (**2n**)*: White solid; m.p. 64–67 °C; ^{1}H NMR ($CDCl_3$): δ = 0.86–0.94 (m, 9H), 1.40–1.53 (m, 2H), 1.72 (brs, 1H), 1.94 (dt, J = 1.3, 10.0 Hz, 1H), 2.15 (t, J = 13.0 Hz, 1H), 2.46 (dt, J = 2, 4.6 Hz, 1H), 2.60 (dd, J = 3.0, 13.0 Hz, 1H), 3.47 (s, 1H), 4.12 ppm (dd, J = 7.0, 11.5 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ = 24.4, 27.15, 32.7, 35.2, 40.95, 50.4, 75.0, 211.9 ppm; IR: $\tilde{\nu}$ = 3490, 2971, 2872, 1728, 1678, 1480, 1451, 1429, 1331, 1161, 1119, 1059, 963, 858, 747 cm^{-1}; HR-EI: calcd for $C_{10}H_{18}O_2$: 170.1307 $[M]^+$; found: 170.1307.

Configuration of **2m** and **2n** were confirmed by observation of the NOE between ^{1}H NMR spectroscopic signals of axial protons at C2, C4, and C6 in **2m**, and at C2, C4, and C6 in **2n** (Figure 2).

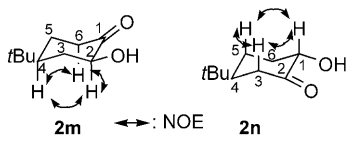


Figure 2. NOE experiment of **2m** and **2n**.

*Oxidation of **1g***: After the solvent had been removed in vacuo, dichloromethane (5 mL), 4-dimethylaminopyridine (1.7 mmol), and benzoylchloride (1.5 mmol) were added to the residue at 0 °C. After the mixture had been stirred for 12 h, aqueous saturated Na_2CO_3 (10 mL) was added. The organic portion was extracted with CH_2Cl_2 (3 × 20 mL). After the organic layer had been dried over $MgSO_4$, the solvent was removed in vacuo. The residue was subjected to silica-gel column chromatography (*n*-hexane/AcOEt 5:1) to afford **2g**.

*Oxidation of **1h***: After the solvent had been removed in vacuo, dichloromethane (10 mL), 4-dimethylaminopyridine (3.4 mmol), and benzoylchloride (3.0 mmol) were added to the residue at 0 °C. After the mixture had been stirred for 12 h, aqueous sat. Na_2CO_3 (20 mL) was added. The organic portion was extracted with CH_2Cl_2 (3 × 20 mL). After the organic layer had been dried over $MgSO_4$, the solvent was removed in vacuo. The residue was subjected to silica-gel column chromatography (*n*-hexane/AcOEt 5:1) to afford **2h**.

Chemical oxidation of 1,2-diols by using V and Br_2: General procedure: Bromine (1.0 mmol) was added dropwise at 0 °C under dark conditions to a solution of 1,2-diol **1e** (0.5 mmol), tin catalyst **V** (0.05 mmol), and K_2CO_3 (1.5 mmol) in methanol (2 mL). After the reaction mixture had been stirred for 30 min, aqueous sat. $Na_2S_2O_3$ (10 mL) was added. The organic portion was extracted with AcOEt (3 × 40 mL). After the organic layer had been dried over $MgSO_4$, the solvent was removed in vacuo. The residue was subjected to silica-gel column chromatography (*n*-hexane/AcOEt 5:1) to afford **2e**.

Chemical oxidation of 1,2-diols by using V and NIS: **General procedure**: NIS (1.0 mmol) was added at 0 °C under dark conditions to a solution of

1,2-diol **1e** (0.5 mmol) and tin catalyst **V** (0.05 mmol) in dichloromethane (2 mL). After the reaction mixture had been stirred for 3 h, aqueous sat. $Na_2S_2O_3$ (10 mL) was added. The organic portion was extracted with chloroform (3×30 mL). After the organic layer had been dried over $MgSO_4$, the solvent was removed in vacuo. The residue was subjected on silica-gel column chromatography (*n*-hexane/AcOEt 5:1) to afford **2e**.

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