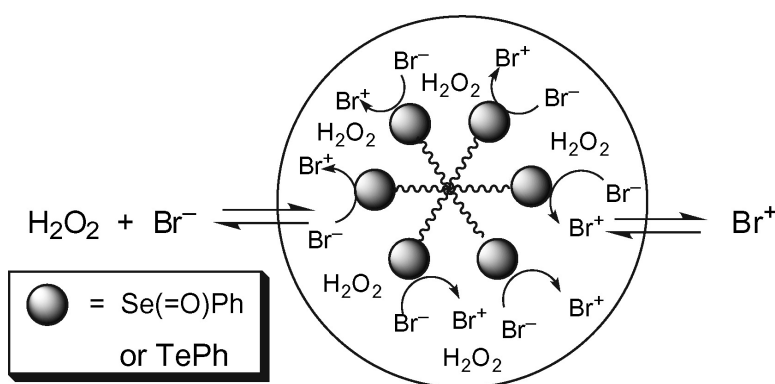


Dendrimeric Organochalcogen Catalysts for the Activation of Hydrogen Peroxide: Origins of the “Dendrimer Effect” with Catalysts Terminating in Phenylseleno Groups

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Dendrimeric Organochalcogen Catalysts for the Activation of Hydrogen Peroxide: Origins of the “Dendrimer Effect” with Catalysts Terminating in Phenylseleno Groups

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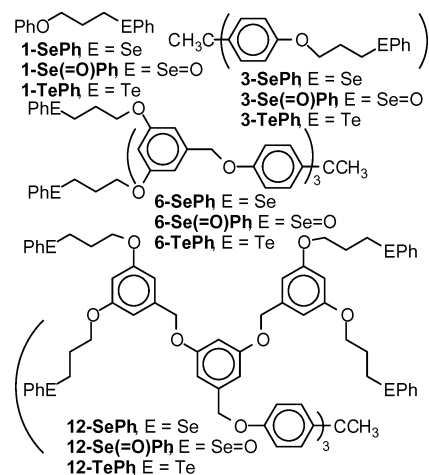
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Abstract: Several scenarios were evaluated to explain the large “dendrimer effect” observed in the bromination of cyclohexene with H_2O_2 and NaBr catalyzed by the addition of Fréchet-type dendrimers terminating in $-\text{O}(\text{CH}_2)_3\text{SePh}$ groups. Although phenylseleninic acid was an efficient catalyst for the oxidation of NaBr with H_2O_2 , first-order rate constants for the selenoxide elimination were too small to produce PhSeO_2H at a rate sufficient to explain the rates of catalysis and no dendrimer effect was observed in the rates of selenoxide elimination. An induction period was observed using **1-SePh** as a catalyst for the oxidation of Br^- with H_2O_2 . The addition of preformed selenoxide **1-Se(=O)Ph** gave immediate catalysis with no induction period. However, rates of oxidation of the selenides with H_2O_2 under homogeneous or biphasic conditions or with *t*-BuOOH under homogeneous conditions were too slow to account for the rates of catalysis, and no dendrimer effect was observed in the rates of oxidation. The primary oxidant for converting selenides to selenoxides was “ Br^{+} ” produced initially by the uncatalyzed background reaction of H_2O_2 with NaBr and then produced catalytically following formation of selenoxide groups. Autocatalysis is observed, and the rate of oxidation increases with the number of SePh groups. Autocatalysis is the source of the large dendrimer effect observed with the SePh series of catalysts.

Introduction

Dendrimer molecules are constructed with a controlled architecture that allows molecular properties to be designed and tailored.¹ This feature is advantageous in the design of dendrimeric catalysts where catalytic functionality can be placed at the termini of the individual arms of the dendrimer² or within the dendrimer architecture.³ In some catalytic systems, a “dendrimer effect” has been observed in which nonstatistical changes in catalytic activity are observed with increasing numbers of catalytic groups.⁴ We have described one of the more striking examples of a dendrimer effect in the catalytic activity of a series of Fréchet-type^{1a,f} dendrimers terminating in phenylchalcogeno groups (Chart 1).^{2c} In the phenyltelluro

Chart 1. Organochalcogenide Catalysts



(TePh) series, the catalytic activity increased statistically with the number of TePh groups and each TePh group had roughly the same reactivity (Figure 1). In contrast, the catalytic activity per SePh group in the phenylseleno (SePh) series increased dramatically as the number of SePh groups per molecule

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- (2) For a few illustrative examples see: (a) Cuadrado, I.; Morán, M.; Casado, C.; Alonso, B.; Lobete, F.; García, B.; Ibistate, M.; Losanda, J. *Organometallics* **1996**, *15*, 5278–5280. (b) Chow, H.-F.; Mak, C. C. *J. Org. Chem.* **1997**, *62*, 5116–5127. (c) Bourque, S. C.; Maltais, F.; Xiao, W.-J.; Tardif, O.; Alper, H.; Arya, P. *J. Am. Chem. Soc.* **1999**, *121*, 3035–3038. (d) Liao, Y.-H.; Moss, J. R. *Organometallics* **1996**, *15*, 4307–4316. (e) Francavilla, C.; Drake, M. D.; Bright, F. V.; Detty, M. R. *J. Am. Chem. Soc.* **2001**, *123*, 57–67.
- (3) For a few illustrative examples see: (a) Zhao, M.; Sun, L.; Crooks, R. M. *J. Am. Chem. Soc.* **1998**, *120*, 4877–4878. (b) Balogh, L.; Tomalia, D. A. *J. Am. Chem. Soc.* **1998**, *120*, 7355–7356. (c) Piotti, M. E.; Rivera, Jr., F.; Bond, R.; Hawker, C. J.; Fréchet, J. M. M. *J. Am. Chem. Soc.* **1999**, *121*, 9471–9472.

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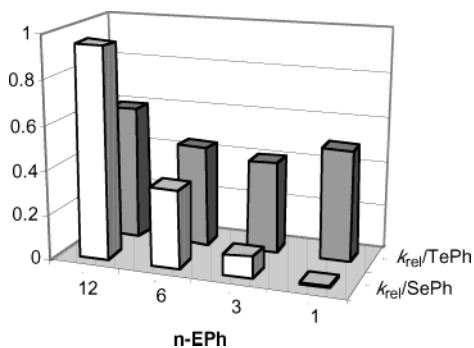
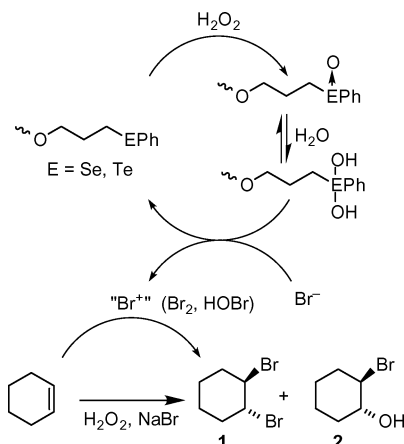


Figure 1. Relative rate constants for catalysis per phenylchalcogeno group, k_{rel}/EPH , in molecules with n arms terminating in phenylchalcogeno groups.

Scheme 1

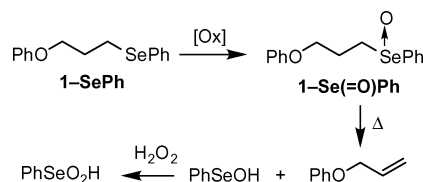


increased. The apparent increase in relative reactivity *per SePh group* is a factor of 75 from 3-phenoxy-1-phenylselenopropane (**1-SePh**) with one SePh group to **12-SePh** with twelve SePh groups.

The reaction of interest in the current work is the bromination of cyclohexene with NaBr and H_2O_2 in the presence of a catalyst from Chart 1 in a two-phase system of CH_2Cl_2 and pH 6 phosphate buffer. The reaction is thought to follow the sequence shown in Scheme 1. In the absence of catalyst, the oxidation of Br^- with H_2O_2 , while thermodynamically favored, is a relatively slow process ($k_{\text{OX}} \approx 1.7 \times 10^{-5} \text{ M}^{-1} \text{ s}^{-1}$),⁵ and brominated products **1** and **2** are formed slowly. The addition of an organochalcogenide catalyst gives oxidation of the chalcogen atom to the corresponding chalcogen oxide, hydration to the dihydroxychalcogenane, introduction of Br^- as a ligand, and, finally, reductive elimination of “ Br^+ ” (as Br_2 or BrOH) and chalcogen(II) compound to start the cycle over. Typically, organotellurides are much more active catalysts than the corresponding selenide. The TePh series in Figure 1 illustrates the “expected” behavior of dendrimeric catalysts with statistical increases in catalytic activity as the catalytic group number per dendrimer increases.

Significantly greater than statistical increases in reaction rates were observed as the number of catalytic groups in the SePh series increased. This trend requires cooperativity either (1) to accelerate the rate-determining step of the catalytic cycle for each SePh group or (2) to accelerate the formation of a new catalytic group that is a more efficient catalyst for H_2O_2 than

Scheme 2



the SePh group. For many organochalcogenide catalysts containing a single organochalcogenide group, the rate of oxidation with H_2O_2 is the rate-determining step.⁶ Should the dendrimer architecture accelerate the oxidation of selenides to selenoxides to a greater extent than the oxidation of the corresponding tellurides, then the rate of oxidation might be responsible for the dendrimer effect.

The catalytic activity of either organoselenides or organotellurides with H_2O_2 is presumed to involve the corresponding selenoxides or telluroxides, respectively. The *syn*-elimination of an organoselenenic acid (RSeOH) from a selenoxide with β -hydrogens to produce an olefin⁷ has no parallel reaction for telluroxides. While no appreciable selenoxide elimination has been observed previously in reactions of **1-SePh**, **3-SePh**, **6-SePh**, or **12-SePh** with H_2O_2 ,^{2e} some selenoxide elimination, as illustrated in Scheme 2 for **1-SePh**, cannot be rigorously excluded. Under the conditions of reaction, any PhSeOH produced from selenoxide elimination would be rapidly oxidized by H_2O_2 to phenylseleninic acid (PhSeO_2H),⁸ which then might function as a catalyst for H_2O_2 .^{9–11} If the dendrimers with a greater number of SePh groups were to produce more PhSeO_2H as a catalyst for H_2O_2 than molecules with fewer SePh groups, then the dendrimer effect might result from these differences.

The effects of the dendrimer architecture on the rates of oxidation and the rates of production of PhSeO_2H were our starting points for the evaluation of the dendrimer effect. We examined PhSeO_2H as a catalyst for the oxidation of Br^- with H_2O_2 , and we examined the rate of oxidation of selenides to selenoxides **1-Se(=O)Ph**, **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph** as well as the rate of selenoxide elimination in these same systems.

Results and Discussion

Phenylseleninic Acid as a Catalyst for the Oxidation of Bromide with H_2O_2 . In our earlier studies,^{2e} we did not see formation of allyl ethers by ^1H NMR spectroscopy in the time course of our reactions as evidence for selenoxide elimination. However, if the catalytic activity of PhSeO_2H were sufficiently great, even a small amount of PhSeO_2H produced by selenoxide elimination might be responsible for the dendrimer effect observed in the SePh series of Chart 1. If PhSeO_2H were the

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active catalyst, then changes in dendrimer architecture across the SePh series should impact the rate of formation of PhSeO₂H either through the rate of elimination of the selenoxide, k_{ELIM} , or through the rate of oxidation of the selenide to the selenoxide, k_{OX} . While seleninic acids have not been previously described as catalysts for halide salt oxidation with H₂O₂, they have been efficient catalysts for H₂O₂ activation in other reactions including epoxidations,⁸ oxidation of sulfides to sulfoxides and sulfones,⁸ Baeyer–Villiger oxidations,⁹ oxidation of aldehydes to carboxylic acids,^{9c} and oxidation of thiols to disulfides.¹⁰

Phenylseleninic acid was evaluated as a catalyst for the oxidation of Br[−] with H₂O₂ in the two-phase system under conditions described in our earlier work.^{2e} The oxidation of Br[−] with H₂O₂ in control experiments (no catalyst) was followed by the rate of bromination of cyclohexene as shown in Scheme 1 to give *trans*-1,2-dibromocyclohexane (**1**) and *trans*-2-bromocyclohexanol (**2**) in a two-phase system of 0.5 M cyclohexene in CH₂Cl₂ for the organic phase and an aqueous phase of H₂O₂ (3.0 M) and NaBr (2.0 M) in pH 6 phosphate buffer (0.1 M) at 298.0 ± 0.1 K. The concentrations of cyclohexene and Br[−] remain essentially unchanged over the course of reaction as H₂O₂ is consumed. The pseudo-first-order rate constant, k_{OBS} , for the appearance of products in the uncatalyzed or control reaction (k_{CONTR}) was (5.8 ± 0.1) × 10^{−5} s^{−1} for the average of triplicate runs (± standard deviation). In the catalyzed reaction, k_{OBS} has contributions from the control and the catalyzed processes. A rate constant for catalysis, k_{CAT} , can be calculated from k_{OBS} for the catalyzed reaction according to

$$k_{\text{OBS}} = k_{\text{CAT}}[\text{Br}^-][\text{catalyst}] + k_{\text{CONTR}} \quad (1)$$

which rearranges to

$$k_{\text{CAT}} = \frac{k_{\text{OBS}} - k_{\text{CONTR}}}{[\text{Br}^-][\text{catalyst}]} \quad (2)$$

The addition of 2.3 × 10^{−3} M PhSeO₂H in the organic phase accelerated the appearance of brominated products with k_{OBS} of (3.4 ± 0.3) × 10^{−4} s^{−1} for the average of triplicate runs. The reaction followed pseudo-first-order kinetics as shown in Figure 2. According to eq 2, the rate constant for catalysis, k_{CAT} for PhSeO₂H, is (6.1 ± 0.5) × 10^{−2} M^{−2} s^{−1}. From 100 mmol of H₂O₂, 3.4 mmol of brominated products was produced from excess cyclohexene in both the catalyzed and uncatalyzed reactions, which is consistent with our earlier work with the catalysts of Chart 1.^{2e}

If PhSeO₂H were the actual catalyst in the dendrimer-catalyzed reaction of Scheme 1, then values of k_{CAT} for the dendrimer would be less than or equal to (in the case of complete selenoxide elimination) a multiple of the number of dendrimer arms (n) and k_{CAT} for PhSeO₂H. This is true for **1-SePh**-, **3-SePh**-, and **6-SePh**-catalyzed reactions (k_{CAT} of 1.2 × 10^{−3}, 2.8 × 10^{−2}, and 2.1 × 10^{−1} M^{−2} s^{−1}, respectively, although the reported value for **1-SePh** is inaccurate on the basis of the work described herein),^{2e} where the observed catalysis is a fraction of the value predicted by the quantity $nk_{\text{CAT}}(\text{PhSeO}_2\text{H})$: 6.2 × 10^{−2}, 1.2 × 10^{−1}, and 3.7 × 10^{−1} M^{−2} s^{−1}, respectively. Partial selenoxide elimination to generate PhSeO₂H could be responsible for the observed catalysis; however, k_{CAT} (1.08 M^{−2} s^{−1})^{2e} for the **12-SePh**-catalyzed reaction is higher

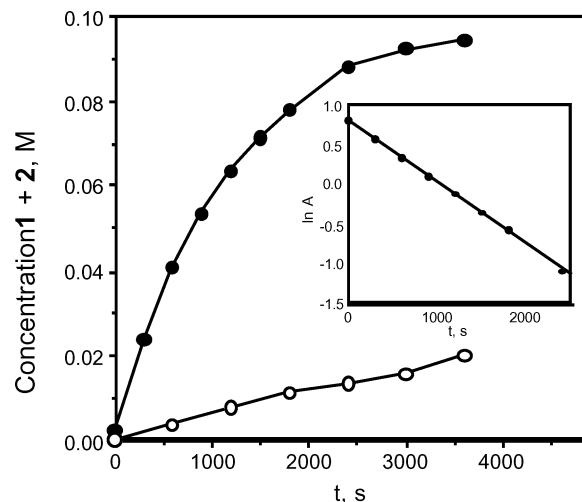


Figure 2. Rate of the appearance of products in the PhSeO₂H-catalyzed (2.3 × 10^{−3} M) bromination of cyclohexene (0.5 M in CH₂Cl₂) with 3 M H₂O₂ and 2.0 M NaBr in pH 6 phosphate buffer (filled circles) relative to the uncatalyzed reaction (open circles). The inset shows the first-order plot of the data where $\ln A = \ln(A_{\infty} - A_t)$, where A_{∞} is the concentration at infinity and A_t is the concentration at time t .

than $nk_{\text{CAT}}(\text{PhSeO}_2\text{H})$ (7.3 × 10^{−1} M^{−2} s^{−1}), which suggests that the reaction is not being catalyzed by PhSeO₂H alone even with complete selenoxide elimination.

Rate of Selenoxide Elimination in Oxidized Catalysts. For the selenide catalysts of Chart 1, PhSeO₂H can only be produced following selenoxide elimination of PhSeOH and subsequent oxidation. The rates of selenoxide elimination, k_{ELIM} (Scheme 2), in oxidized **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** were measured by ¹H NMR spectroscopy. The selenides were oxidized to the corresponding selenoxides **1-Se(=O)Ph**, **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph** either with *N*-chlorosuccinimide¹² followed by hydrolysis of the intermediate chloroselenonium salt or with H₂O₂. Both procedures gave the same oxidized product. ¹H NMR and mass spectra for **1-Se(=O)Ph**, **3-Se(=O)Ph**, and **6-Se(=O)Ph** (Figures S1–S3) and the ¹H NMR spectrum for **12-Se(=O)Ph** (Figure S4) are compiled in the Supporting Information.

Selenoxide elimination in oxidized **1-Se(=O)Ph** produces allyl phenyl ether and PhSeOH as shown in Scheme 2. For **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph**, selenoxide elimination leads to multiple allyl aryl ether groups and PhSeOH. The rates of selenoxide elimination in **1-Se(=O)Ph**, **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph** were determined by the rate of olefinic proton appearance for the allyloxy groups by ¹H NMR spectroscopy. For **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph**, the 12 aromatic protons of the 1,1,1-tris(4-hydroxyphenyl)ethyl core served as a 12-proton internal standard (Figure S5, Supporting Information). The chemical shifts of the AA'BB' pattern were separated from all other aromatic and olefinic signals in reduced, oxidized, and eliminated forms. For **1-Se(=O)Ph**, the entire aromatic region was integrated as a 10-proton internal standard. Rate constants for selenoxide elimination, k_{ELIM} , at 323.0 ± 0.3 K in CDCl₃ are compiled in Table 1 and represent the average of duplicate runs.

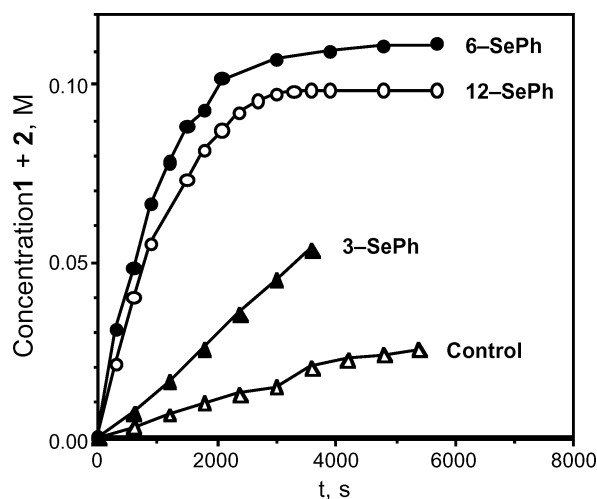
Oxidation of **3-SePh**, **6-SePh**, and **12-SePh** to **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph**, respectively, gives polyselenoxides, and each sequential elimination of PhSeOH

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Table 1. Rate Constants for Selenoxide Elimination (k_{ELIM}), Oxidation with $t\text{-BuOOH}$ [$k_{\text{OX}}(t\text{-BuOOH})$], and Oxidation with H_2O_2 [$k_{\text{OX}}(\text{H}_2\text{O}_2)$] and the Rate Constant for Catalysis (k_{CAT}) for Selenides/Selenoxides Derived from **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh**

| compd | $k_{\text{ELIM}}^{a,b}$ s^{-1} | $k_{\text{OX}}(t\text{-BuOOH})^{a,c}$ $\text{M}^{-1}\text{s}^{-1}$ | $k_{\text{OX}}(\text{H}_2\text{O}_2)^{c,d}$ $\text{M}^{-1}\text{s}^{-1}$ | k_{CAT}^e $\text{M}^{-2}\text{s}^{-1}$ |
|----------------------------|--|---|---|--|
| 1-SePh/1-Se(=O)Ph | $(5.6 \pm 0.9) \times 10^{-4}$ | $(1.85 \pm 0.01) \times 10^{-3}$ | $(8.1 \pm 0.5) \times 10^{-6}$ | $(2.2 \pm 0.1) \times 10^{-2f}$ |
| 3-SePh/3-Se(=O)Ph | $(5.60 \pm 0.01) \times 10^{-4}$ | $(1.96 \pm 0.04) \times 10^{-3}$ | $(1.3 \pm 0.1) \times 10^{-5}$ | 2.8×10^{-2g} |
| 6-SePh/6-Se(=O)Ph | $(5.7 \pm 0.2) \times 10^{-4}$ | $(2.40 \pm 0.04) \times 10^{-3}$ | $(1.0 \pm 0.1) \times 10^{-5}$ | 2.1×10^{-1g} |
| 12-SePh/12-Se(=O)Ph | $(6.20 \pm 0.08) \times 10^{-4}$ | $(2.38 \pm 0.08) \times 10^{-3}$ | $(1.8 \pm 0.5) \times 10^{-5}$ | 1.08^g |

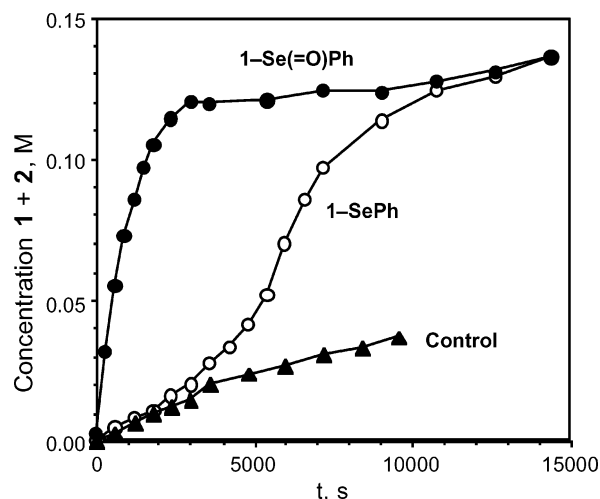
^a In CDCl_3 at 323.0 ± 0.3 K. ^b Average of duplicate runs. ^c 0.5 M $t\text{-BuOOH}$. ^d In a two-phase mixture of CDCl_3/pH 6 phosphate buffer containing 3.4 M H_2O_2 . ^e 0.5 M cyclohexene in $\text{CH}_2\text{Cl}_2/\text{pH}$ 6 phosphate buffer containing 3.0 M H_2O_2 and 2.0 M NaBr. Calculated according to eq 2. ^f Average of triplicate runs (\pm standard deviation). ^g Reference 2e.

**Figure 3.** Rate of the appearance of products in the bromination of cyclohexene (0.5 M in CH_2Cl_2) with 3 M H_2O_2 and 2.0 M NaBr in pH 6 phosphate buffer catalyzed with **3-SePh**, **6-SePh**, or **12-SePh**.

produces a “new” compound that might impact the rate of elimination of the next selenoxide group. The structural differences generated by sequential elimination of each selenoxide had essentially no impact on the rates of elimination. A single rate was observed, within our measurement precision, throughout the selenoxide elimination in **3-Se(=O)Ph**, **6-Se(=O)Ph**, or **12-Se(=O)Ph**. Furthermore, the different monomer and dendrimer architectures among **1-Se(=O)Ph**, **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph** had little impact on k_{ELIM} . At 323 K in CDCl_3 , the rates of selenoxide elimination for all four compounds were nearly identical (5.6×10^{-4} to $6.2 \times 10^{-4} \text{ s}^{-1}$) with a half-life of approximately 1200 s. At 298 K in the $\text{CH}_2\text{Cl}_2/\text{pH}$ 6 buffer mixture, the rate of elimination was much slower with half-lives in excess of 10^4 s.

Oxidation of **1-TePh** either with N -chlorosuccinimide¹² followed by hydrolysis of the intermediate chlorotelluronium salt or with H_2O_2 gave **1-Te(=O)Ph**. In contrast to the thermal lability of **1-Se(=O)Ph**, **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph**, the telluroxide was quite stable and no elimination products were observed with **1-Te(=O)Ph** even after 6 h at 323 K.

Selenoxide Elimination and Catalysis. On the basis of values of k_{ELIM} , if the active catalyst for the reaction of Scheme 1 from **3-SePh**, **6-SePh**, or **12-SePh** were derived from selenoxide elimination, then an induction period (>1200 s) should be observed prior to the maximum reaction velocity to accommodate oxidation of the selenide, selenoxide elimination, and oxidation of PhSeOH to PhSeO_2H . As shown in Figure 3, the addition of **3-SePh**, **6-SePh**, or **12-SePh** to a two-phase mixture of 0.5 M cyclohexene in CH_2Cl_2 and 2.0 M NaBr and

**Figure 4.** Rate of the appearance of products in the bromination of cyclohexene (0.5 M in CH_2Cl_2) with 3 M H_2O_2 and 2.0 M NaBr in pH 6 phosphate buffer catalyzed by 2.8×10^{-2} M **1-SePh** (open circles) or 2.8×10^{-2} M **1-Se(=O)Ph** (filled circles).

3.0 M H_2O_2 in pH 6 phosphate buffer at 296.0 ± 0.1 K gave immediate formation of brominated products **1** and **2** at a rate faster than the uncatalyzed rate with no apparent induction period during the time intervals we were able to sample.

Our first insight into the actual catalytic functional group using **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** as catalysts came from the product vs time profile using **1-SePh** as a catalyst. In our original work, the concentration of **1-SePh** was 2.5×10^{-3} M and the contribution from the uncatalyzed reaction to the overall velocity was greater than that of the catalyzed reaction under these conditions.^{2e} We were not surprised by this since selenides typically are much poorer catalysts than the corresponding tellurides.¹³ We reexamined the reaction of Scheme 1 using a higher concentration of **1-SePh** (2.8×10^{-2} M) and found some surprising results. Specifically, during the initial 1 h of reaction, the rate of appearance of products was slow [k_{OBS} of $(6.3 \pm 0.1) \times 10^{-5} \text{ s}^{-1}$ at 298 K based on the average of duplicate runs with 2.8×10^{-2} M **1-SePh**], nearly identical to that observed with 2.5×10^{-3} M **1-SePh**, and only slightly greater than the uncatalyzed background rate ($5.8 \times 10^{-5} \text{ s}^{-1}$) as shown in Figure 4. After 1 h, the rate of appearance of brominated products accelerated. The lack of an increase in the initial rate at a much higher concentration of **1-SePh** and the apparent induction period suggested that **1-SePh** was not the active catalyst in the system.

The induction period observed with **1-SePh** was not related to selenoxide elimination. When **1-SePh** in CH_2Cl_2 was stirred

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with 3.0 M H₂O₂ and 2.0 M NaBr in pH 6 phosphate buffer, the oxidation to the selenoxide was complete after 1 h. However, no allyl phenyl ether was detected in the organic phase by ¹H NMR spectroscopy. Shaking a CH₂Cl₂ solution of the selenoxide **1-Se(=O)Ph** with 5% aqueous sodium bisulfite gave reduced **1-SePh** in nearly quantitative recovered yield. These results suggest that selenoxide elimination is not important in the formation of the active catalyst with **1-SePh**.

The Selenoxide as Catalyst. One alternative to the selenoxide elimination generating the active catalyst with **1-SePh** is that oxidation of **1-SePh** to **1-Se(=O)Ph** is responsible for the induction period observed in Figure 4 and that **1-Se(=O)Ph** is the actual catalyst in the system. It is known that selenoxides catalyze the decomposition of H₂O₂ to give O₂ and H₂O,¹⁴ indicating that selenoxides interact with H₂O₂ in solution.

When **1-Se(=O)Ph** was prepared by oxidation of **1-SePh** with either *N*-chlorosuccinimide¹² or H₂O₂ and added to the two-phase mixture of cyclohexene, NaBr, and H₂O₂, no induction period was observed as shown in Figure 4 and pseudo-first-order kinetics were followed. Furthermore, in the absence of H₂O₂, 0.1 M solutions of selenoxide gave no bromination of 0.5 M cyclohexene in CH₂Cl₂ after 24 h of stirring with 2 M NaBr in pH 6 phosphate buffer. These results suggest that the actual catalyst in bromide oxidation is the selenoxide and *not* the selenide. For 2.8×10^{-2} M **1-Se(=O)Ph**, k_{OBS} was $(1.28 \pm 0.05) \times 10^{-3} \text{ s}^{-1}$ based on the average of triplicate runs, which corresponds to k_{CAT} of $(2.2 \pm 0.1) \times 10^{-3} \text{ M}^{-2} \text{ s}^{-1}$ for **1-Se(=O)Ph** according to eq 2.

Oxidation of Organochalcogenide Compounds. Typically, organotellurides are oxidized much more rapidly than the corresponding organoselenides with a variety of oxidants.¹⁵ The rates of oxidation of monotellurides **1-TePh** and **1-SePh** with H₂O₂ were followed in a stopped-flow spectrometer under pseudo-first-order conditions. Final concentrations of 1.03×10^{-3} M chalcogenide and 1.03×10^{-2} M H₂O₂ at 276.8 ± 0.4 K gave observed rate constants for oxidation of $(1.10 \pm 0.01) \times 10^{-1} \text{ s}^{-1}$ for **1-TePh** and $(1.20 \pm 0.01) \times 10^{-6} \text{ s}^{-1}$ for **1-SePh** based on the average of 7–10 independent runs, which correspond to second-order rate constants of $10.7 \pm 0.1 \text{ M}^{-1} \text{ s}^{-1}$ for **1-TePh** and $(1.2 \pm 0.1) \times 10^{-4} \text{ M}^{-1} \text{ s}^{-1}$ for **1-SePh** in MeOH. On the basis of these rate constants, oxidation of the Te atoms of the TePh series under the conditions of Scheme 1 would be $\geq 95\%$ complete within 1 s while the half-life for the oxidation of the Se atoms of the SePh series would be on the order of 5×10^3 s.

The data shown in Figure 3 clearly indicate that no induction period is observed with **3-SePh**, **6-SePh**, or **12-SePh** as catalyst. Hence, if a selenoxide functionality were the actual catalytic group in these systems, the lack of an induction period would suggest that oxidation is much more rapid in the dendrimeric selenides relative to **1-SePh**. Although the lack of dendrimer solubility in MeOH precluded measurement of the rates of oxidation under the conditions described above, the oxidations of **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** were followed under homogeneous conditions using *tert*-butyl hydroperoxide (*t*-BuOOH) as oxidant in CDCl₃.

Oxidation of the SePh Series with *t*-BuOOH as Oxidant. The progress of oxidation of **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** with excess *t*-BuOOH in CDCl₃ was easily monitored by ¹H NMR spectroscopy. The SePh group *ortho* protons were diagnostic for SePh group oxidation to the corresponding Se(=O)Ph group. As the SePh group, the *ortho* protons appeared in the chemical shift range δ 7.4–7.5. As the Se(=O)Ph group, the phenyl ring *ortho* protons appeared at δ 7.7. As before, the 12 aromatic protons of the 1,1,1-tris(4-hydroxyphenyl)ethyl core served as a 12-proton internal standard to determine **3-Se(=O)Ph/3-SePh**, **6-Se(=O)Ph/6-SePh**, and **12-Se(=O)Ph/12-SePh** ratios while the two Se(=O)Ph group *ortho* protons were integrated against the remaining eight aromatic protons to determine **1-Se(=O)Ph/1-SePh** ratios.

The concentrations of **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** were adjusted to keep the concentration of SePh groups constant at 2.5×10^{-3} M, and the concentration of *t*-BuOOH was kept constant at 5×10^{-2} M. While the large excess of *t*-BuOOH allowed pseudo-first-order kinetics to be followed, the excess oxidant was also necessary to have oxidation occur within a practical time frame.

At ambient temperature, the half-lives for oxidation under these conditions were all > 5 h for **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** and some selenoxide elimination was observed. At 323.0 ± 0.3 K, selenoxide elimination was fast relative to the rate of oxidation, $k_{\text{OX}}(t\text{-BuOOH})$, no buildup of selenoxide was observed, and $k_{\text{OX}}(t\text{-BuOOH})$ was determined from the rate of appearance of the olefinic protons from the allyloxy groups as described above. Values of $k_{\text{OX}}(t\text{-BuOOH})$ at 323 K in CDCl₃ are compiled in Table 1 and represent the average of duplicate runs. The observed pseudo-first-order rate constants for oxidation were similar and fell in the range 9.25×10^{-5} to $1.20 \times 10^{-4} \text{ s}^{-1}$, which correspond to second-order rate constants of 1.85×10^{-3} to $2.40 \times 10^{-3} \text{ M}^{-1} \text{ s}^{-1}$ at 323 K (Table 1). Nominal increases in the rate of oxidation were observed in the order **1-SePh** < **3-SePh** < **6-SePh** \approx **12-SePh**.

Oxidation of the SePh Series with H₂O₂ in the Two-phase Mixture CDCl₃/pH 6 Buffer. The increases in rate observed under homogeneous conditions did not account for the dendrimer effect observed in catalysis for the SePh series. The rates of oxidation with H₂O₂ were also measured under pseudo-first-order conditions in a two-phase system of CDCl₃ and 3.4 M H₂O₂ in pH 6 phosphate buffer using ¹H NMR spectroscopy on aliquots of the reaction mixture over the first 6×10^3 s of reaction. At 296 ± 1 K, pseudo-first-order kinetics were followed and values of k_{OBS} for the oxidation were 2.9×10^{-5} to $5.3 \times 10^{-5} \text{ s}^{-1}$, which correspond to second-order rate constants of 8.1×10^{-6} to $1.8 \times 10^{-5} \text{ M}^{-1} \text{ s}^{-1}$ (Table 1). Again, the rates of oxidation in the two-phase system of CDCl₃ and 3.4 M H₂O₂ in pH 6 phosphate buffer at 298 K in the absence of bromide were too slow to accommodate the observed kinetic profile of catalysis with half-lives for oxidation of $> 10^4$ s for all four compounds **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh**.

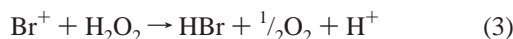
Oxidation with H₂O₂ and Bromide. Br⁺ as Oxidant. While the oxidation of the organotelluride catalysts with H₂O₂ is rapid and essentially complete within 1 s for the conditions of reaction studied here, the oxidation of selenides to selenoxides with H₂O₂ is too slow to accommodate the observed kinetics for cyclohexene bromination. Furthermore, the dendrimer architecture did not accelerate the SePh series rate of oxidation with H₂O₂

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(or *t*-BuOOH) to the extent necessary to explain the dendrimer effect observed in catalysis. One is left with the conclusion that the Br^+ species formed in the background reaction must be responsible for the initial oxidation of the selenide groups to the corresponding selenoxides. Sources of Br^+ (Br_2 , BrOH) oxidize Se(II) to Se(IV) with significantly larger second-order rate constants for oxidation than H_2O_2 .¹⁵ The production of Br^+ in the background reaction is sufficient to oxidize the organoselenides to the corresponding selenoxides.

In the uncatalyzed reaction shown in Scheme 1, a combined 3.4 mmol of brominated products **1** and **2** was produced from 100 mmol of H_2O_2 with an observed rate constant of $5.8 \times 10^{-5} \text{ s}^{-1}$ for production of **1** and **2**. All 100 mmol of H_2O_2 is consumed in this process.^{2c} In the oxidation of Br^- with H_2O_2 , the bulk of the H_2O_2 is decomposed by the Br^+ that is produced according to eq 3.¹⁶ The initial concentration of H_2O_2 is 3 M,



and the initial velocity for consumption of H_2O_2 is $1.7 \times 10^{-4} \text{ M s}^{-1}$ based on k_{CONTR} for the background reaction of $5.8 \times 10^{-5} \text{ s}^{-1}$. As discussed above, k_{CONTR} includes the Br^- concentration of 2 M, which is assumed to remain essentially constant during the reaction. However, if only 3.4% of this Br^+ is captured by substrate, the "effective" initial velocity for production of Br^+ is approximately $5.8 \times 10^{-6} \text{ M s}^{-1}$.

For the $2.8 \times 10^{-2} \text{ M}$ **1-SePh** used to generate the data of Figure 4, the background reaction alone from 3 M H_2O_2 and 2 M NaBr would produce enough Br^+ to oxidize all of the selenide in approximately $5 \times 10^3 \text{ s}$. As shown in Figure 4, the rate of bromination of cyclohexene reaches a maximum at approximately $5 \times 10^3 \text{ s}$, which is consistent with this analysis. The data of Figure 3 show no induction period for catalysis of the bromination of cyclohexene with **3-SePh**, **6-SePh**, or **12-SePh**. Oxidation of the $2.5 \times 10^{-3} \text{ M}$ **3-SePh** ($7.5 \times 10^{-3} \text{ M}$ in SePh groups), $2.5 \times 10^{-3} \text{ M}$ **6-SePh** ($1.5 \times 10^{-2} \text{ M}$ in SePh groups), and $4 \times 10^{-4} \text{ M}$ **12-SePh** ($4.8 \times 10^{-3} \text{ M}$ in SePh groups) used in these reactions with 3.0 M H_2O_2 and 2.0 M NaBr would require between 1×10^3 and $2 \times 10^3 \text{ s}$ to generate sufficient Br^+ via the background reaction alone. However, each SePh group that is oxidized to a Se(=O)Ph group produces a new catalytic site capable of generating Br^+ from H_2O_2 and NaBr, and one might expect the oxidation to be autocatalytic.

The rates of oxidation of **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** in a two-phase mixture of CDCl_3 and 3.0 M H_2O_2 and 2.0 M NaBr in pH 6 phosphate buffer were determined by ^1H NMR spectroscopy at $296 \pm 1 \text{ K}$. As shown in Figure 5, the rate constant for catalysis increases with time for all four systems and initial rate constants for oxidation increase with the number of SePh groups. Oxidation was $\sim 95\%$ complete for **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** after 3.6×10^3 , 2.4×10^3 , $< 6 \times 10^2$, and $< 1.2 \times 10^2 \text{ s}$, respectively. For each of these reactions, the concentration of SePh groups was held constant at approximately $1 \times 10^{-2} \text{ M}$.

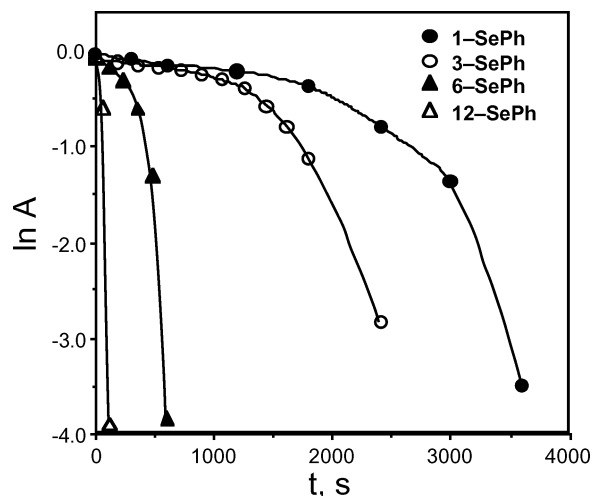


Figure 5. Autocatalytic behavior of the oxidation of **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** with 3.0 M H_2O_2 and 2.0 M NaBr in a two-phase mixture of CDCl_3 and pH 6 phosphate buffer at $296 \pm 1 \text{ K}$, where $\ln A = \ln(A_\infty - A_t)$, where A_∞ is the concentration at infinity and A_t is the concentration at time t .

Reaction of Cyclohexene with NaBr and 3-Se(=O)Ph. In earlier work, we demonstrated that diorganodihydroxyselenium(IV) and -tellurium(IV) compounds were mechanistically similar as oxidants, but that the rate constants associated with Se(IV) species were several orders of magnitude slower than those associated with Te(IV) species.^{15b,17} We examined the bromination of cyclohexene with preformed **3-Se(=O)Ph** (0.1 M) in $\text{CH}_2\text{Cl}_2/\text{pH 6 phosphate buffer}$ containing 2 M NaBr. After 24 h, no bromination products were detected by gas chromatography, which indicates that the $\text{Se(II)}/\text{Se(IV)}$ redox cycle does not contribute in any significant way to the bromination of cyclohexene with H_2O_2 and NaBr. The formation of brominated products is due to the selenoxide-catalyzed reaction and the uncatalyzed background reaction.

Summary and Conclusions

The dendrimeric organoselenides and -tellurides of Chart 1 catalyze the oxidation of Br^- with H_2O_2 by two completely different mechanisms. The dendrimeric *organotellurides* are rapidly oxidized to the corresponding dendrimeric organotelluroxides with H_2O_2 under the conditions of reaction. On the basis of the second-order rate constant of $10.7 \text{ M}^{-1} \text{ s}^{-1}$ for the oxidation of **1-TePh** with H_2O_2 , the oxidations of **1-TePh**, **6-TePh**, and **12-TePh** would all be $\geq 95\%$ complete in $\leq 1 \text{ s}$! Subsequent reaction of the telluroxide with Br^- produces Br^+ and reduced telluride, which is rapidly reoxidized to continue the catalytic cycle as shown in Scheme 1 for $\text{E} = \text{Te}$.

In contrast, the dendrimeric *organoselenide*-catalyzed reactions with H_2O_2 differ in three significant ways from the corresponding organotelluride systems: (1) Oxidations with H_2O_2 are much slower with half-lives on the order of several hours. (2) The catalyst in these systems is the selenoxide oxidation state [Se(IV)] and not the selenide oxidation state [Se(II)]. (3) The actual oxidant in the selenide-catalyzed reaction is the Br^+ that is initially generated via the uncatalyzed background reaction and then by selenoxide-catalyzed processes

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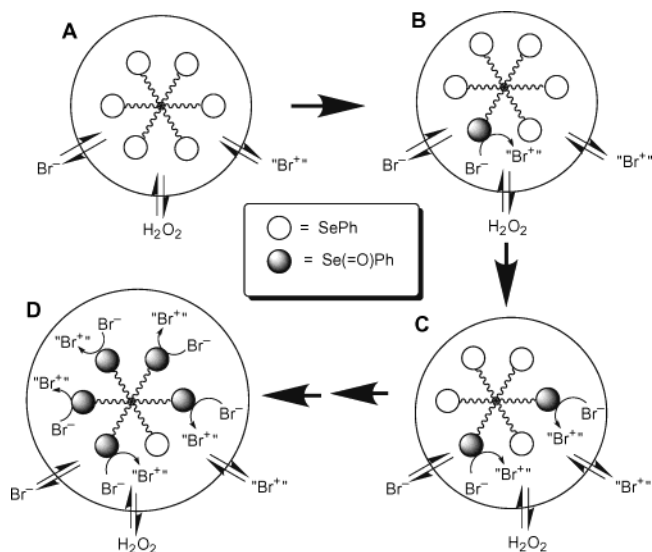
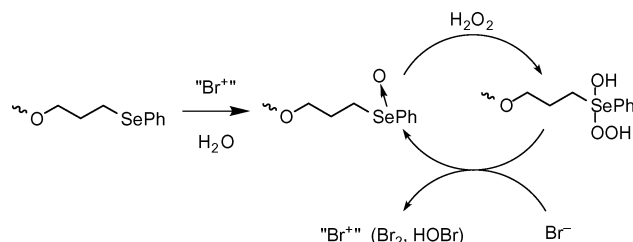


Figure 6. A cartoon representation for the autocatalytic oxidation of dendrimeric polyorganoselenides. The large circles enclosing the dendrimers represent the local environment around the dendrimer (the “dendrimer sphere” as opposed to the bulk solution). (A) Br^+ diffuses into the dendrimer sphere or is generated via reaction of H_2O_2 and Br^- that have diffused into the dendrimer sphere. (B) Oxidation of the first selenide generates a selenoxide group that begins the catalyzed reaction of H_2O_2 and Br^- within the dendrimer sphere. The oxidation of the second selenide is accelerated by the higher local concentration of Br^+ , even though it is diffusing into the bulk solution. (C) The process is repeated with an accelerated rate for the next oxidation. (D) Oxidation of the final selenide group will have the fastest rate due to the much higher local concentration of Br^+ , even though it is diffusing into the bulk solution.

Scheme 3



as well. The catalytic cycle for the selenoxide is summarized in Scheme 3.

As shown in Figure 5, the oxidation of the selenides with Br^+ becomes autocatalytic as the reaction progresses and the rate of oxidation increases with the number of catalytic groups. The cartoon of Figure 6 summarizes the process for a polyfunctional dendrimer. Oxidation of the first selenide residue occurs via diffusion of Br^+ into the dendrimer sphere or via the uncatalyzed oxidation of Br^- with H_2O_2 within the dendrimer sphere. The new selenoxide functionality catalyzes the oxidation of more Br^- with H_2O_2 , which can increase the local concentration of Br^+ in two different ways. In one, the “point” production of Br^+ at the catalytic site creates a concentration gradient of Br^+ as it diffuses into the bulk solution. While the initial oxidation of a variety of organoselenides is rapid (k_{OX} of 10^5 – $10^6 \text{ M}^{-1} \text{ s}^{-1}$),¹⁵ it is still slow relative to diffusion. In the second, the microenvironment of the dendrimer may “hold” the Br^+ within the dendrimer sphere by providing a more favorable medium for Br^+ through a combination of polar interactions and/or π -interactions.^{3c,18}

After formation of the first selenoxide group in the dendrimer, oxidation of the next SePh group is accelerated due to the

increased production of Br^+ . Each sequential oxidation is accelerated due to further increases in the local Br^+ concentration. The large dendrimer effect observed in the SePh series of dendrimers in Chart 1 is associated with the rate of in situ production of the actual catalyst—namely, the oxidation of the selenide to the corresponding selenoxide.

Since **3-SePh**, **6-SePh**, and **12-SePh** are rapidly oxidized under the conditions of reaction, values of k_{CAT} starting with unoxidized selenide or oxidized selenoxide are identical for **3-Se(=O)Ph/3-SePh**, **6-Se(=O)Ph/6-SePh**, and **12-Se(=O)Ph/12-SePh**. In contrast, the oxidation of **1-SePh** to **1-Se(=O)Ph** is relatively slow. We compared values of k_{CAT} for **3-SePh**, **6-SePh**, and **12-SePh** for the bromination of cyclohexene with k_{CAT} for **1-Se(=O)Ph** to determine whether there was a dendrimer effect associated with the corresponding selenoxides. For **1-Se(=O)Ph**, k_{CAT} was $2.1 \times 10^{-2} \text{ M}^{-2} \text{ s}^{-1}$. From our earlier work,^{2e} k_{CAT} was $2.8 \times 10^{-2} \text{ M}^{-2} \text{ s}^{-1}$ for **3-Se(=O)Ph**, $2.1 \times 10^{-1} \text{ M}^{-2} \text{ s}^{-1}$ for **6-Se(=O)Ph**, and $1.08 \text{ M}^{-2} \text{ s}^{-1}$ for **12-Se(=O)Ph**. In this comparison, the reactivity per catalytic group increases by a factor of 4 from the monomer **1-Se(=O)Ph** to **12-Se(=O)Ph**, which is more typical of other dendrimer effects that have been reported.⁴ The apparent increase in catalytic activity per functional group with increasing numbers of SePh groups in the **1-Se(=O)Ph**, **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph** series is actually the product of the differences in the rate of oxidation of selenides to selenoxides (a factor of roughly 30 due to autocatalysis) as well as a modest dendrimer effect (a factor of 4) for the bromination of cyclohexene.

The selenoxide group appears to be a highly reactive catalytic group for the activation of H_2O_2 in addition to its known catalase-like ability to decompose H_2O_2 .¹⁴ We are currently examining stereoelectronic effects on the efficiency and reactivity of selenoxide catalysts, and we are designing polyfunctional, dendrimeric selenoxides that cannot undergo selenoxide elimination reactions.

Experimental Section

General Methods. Solvents and reagents were used as received from Sigma-Aldrich Chemical Co. (St. Louis, MO). NMR spectra were recorded at 23 °C (unless otherwise noted) on a Varian Gemini-300, Inova 400, or Inova 500 instrument with residual solvent signal as the internal standard: CDCl_3 (δ 7.26 for proton, δ 77.16 for carbon). Compounds **1-TePh**, **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh** were prepared according to ref 2e.

General Procedures for the Oxidation of Selenides. A. Preparation of Selenoxide Catalysts Using NCS. The selenide and *N*-chlorosuccinimide (15.0 equiv/SePh group on the catalyst) were stirred in 1/1 methanol/ CH_2Cl_2 (10 mL/mmol of PhSe groups) at 0 °C for 0.5 h. An equal volume of CH_2Cl_2 and 1.5 times that volume of 10% aqueous NaOH were added to the reaction mixture, and the resulting mixture was stirred for an additional 5 min at ambient temperature. The organic layer was removed, dried with Na_2SO_4 , and concentrated to yield the selenoxide, which was used without further purification.

B. Preparation of Selenoxide Catalysts Using H_2O_2 and NaBr. Sodium bromide (0.412 g, 4.0 mmol, 2.0 M), 30% H_2O_2 (1.0 mL), pH 6.0 phosphate buffer (0.23 M, 1.0 mL), and 0.8 mL of a CDCl_3 stock solution ($\sim 10 \text{ mg/mL}$) of selenide were combined and stirred at room

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temperature for 10 min (**6-SePh** and **12-SePh**) or 100 min (**1-SePh** and **3-SePh**). The CDCl_3 layer was removed and placed into an NMR tube with no further purification.

Data for 1-Se(=O)Ph: ^1H NMR (500 MHz, CDCl_3) δ 7.72 (d, 2 H, $J = 1.5, 8.0$ Hz), 7.48–7.53 (m, 3 H), 7.26 (t, 2 H, $J = 8.0$ Hz), 6.94 (t, 1 H, $J = 7.5$ Hz), 6.84 (d, 2 H, $J = 8.5$ Hz), 3.98–4.05 (m, 2 H), 3.03–3.08 (m, 1 H), 2.93–2.98 (m, 1 H), 2.24–2.32 (m, 1 H), 2.00–2.08 (m, 1 H); ESMS m/z 309 ($\text{C}_{15}\text{H}_{16}\text{O}_2^{80}\text{Se} + \text{H}^+$). Anal. Calcd for $\text{C}_{15}\text{H}_{16}\text{O}_2\text{Se}$: C, 58.64; H, 5.25. Found: C, 59.04; H, 5.52.

Data for 3-Se(=O)Ph: ^1H NMR (500 MHz, CDCl_3) δ 7.71 (d, 6 H, $J = 1.5, 8.0$ Hz), 7.48–7.53 (m, 9 H), 6.94 (d, 6 H, $J = 8.5$ Hz), 6.72 (d, 6 H, $J = 9.0$ Hz), 3.95–4.02 (m, 6 H), 3.01–3.06 (m, 3 H), 2.92–2.97 (m, 3 H), 2.22–2.30 (m, 3 H), 2.06 (s, 3 H), 1.99–2.04 (m, 3 H); ESMS m/z 949 ($\text{C}_{47}\text{H}_{48}\text{O}_6^{80}\text{Se}_3 + \text{H}^+$).

Data for 6-Se(=O)Ph: ^1H NMR (500 MHz, CDCl_3) δ 7.70 (d, 12 H, $J = 1.5, 8.0$ Hz), 7.46–7.52 (m, 18 H), 6.97 (d, 6 H, $J = 9.0$ Hz), 6.81 (d, 6 H, $J = 9.0$ Hz), 6.52 (d, 6 H, $J = 2.0$ Hz), 6.30 (s, 3 H), 4.90 (s, 6 H), 3.95–4.02 (m, 12 H), 3.01–3.06 (m, 6 H), 2.89–2.95 (m, 6 H), 2.23–2.31 (m, 6 H), 2.07 (s, 3 H), 1.98–2.05 (m, 6 H); ESMS m/z 1957 ($\text{C}_{95}\text{H}_{96}\text{O}_{15}^{80}\text{Se}_6 + \text{H}^+$).

Data for 12-Se(=O)Ph: ^1H NMR (500 MHz, CDCl_3) δ 7.69 (d, 24 H, $J = 6.5$ Hz), 7.45–7.50 (m, 36 H), 6.97 (d, 6 H, $J = 8.5$ Hz), 6.83 (d, 6 H, $J = 8.5$ Hz), 6.65 (s, 6 H), 6.51 (s, 15 H), 6.30 (s, 6 H), 4.92 (s, 6 H), 4.91 (s, 12 H), 3.94–4.01 (m, 24 H), 2.99–3.05 (m, 12 H), 2.88–2.93 (m, 12 H), 2.23–2.29 (m, 12 H), 2.08 (s, 3 H), 1.98–2.03 (m, 12 H); no parent ion observed by mass spectrometry.

The oxidized selenides were difficult to characterize due to mixtures of diastereomers (for **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph**) and elimination reactions. A sample of the oxidized material in CH_2Cl_2 (100 mg in 10 mL) was shaken with two 10 mL aliquots of 5% aqueous sodium bisulfite to reduce the selenoxide groups to selenide groups. The organic phase was dried over Na_2SO_4 and concentrated to give **1-SePh**, **3-SePh**, **6-SePh**, and **12-SePh**, respectively, which were identical to authentic materials.²⁶

General Procedure for the Kinetic Analysis of the Bromination of Cyclohexene with 3.0 M H_2O_2 and 2.0 M NaBr in pH 6.0 Phosphate Buffer. Sodium bromide (6.63 g, 0.064 mmol) was added to a stirred (constant-rate, overhead stirrer at 50 rpm with a 2.0 in. stir blade), two-phase mixture of seleninic acid (9.1 mg, 0.048 mmol, 2.3×10^{-3} M), selenide or selenoxide catalyst (except in control reactions where no selenide was added), cyclohexene (4.10 g, 0.050 mmol), and diphenyl ether (20 mg, 1 mg/mL, inert to reaction conditions) in 20 mL of CH_2Cl_2 and an aqueous phase of 20 mL of pH 6.0 phosphate buffer (0.23 M) and 12.5 mL of 30% H_2O_2 (110 mmol) in a constant-temperature bath at 298.0 ± 0.1 K. Aliquots (<1 mL) were withdrawn at the appropriate time, placed in a glass culture tube (13 \times 100 mm), and frozen in a CO_2 /acetone bath. The samples were thawed, and the organic layer was analyzed by gas chromatography. The rate of appearance of brominated products **1** and **2** was compared to that of the internal standard, diphenyl ether. Infinity points for the pseudo-first-order kinetics (constant bromide concentration of 2.0 M) were determined at 48 h for each kinetic run.

A plot of $\ln(A_\infty - A_t)$, where A_∞ is the concentration of brominated products **1** and **2** at infinity and A_t is the concentration of brominated products **1** and **2** at time t , as a function of time is linear with the slope defined as $-k_{\text{OBS}}$. The values in Table 1 are the average of triplicate runs (\pm standard deviation).

Kinetic Analysis of the 1-SePh-Catalyzed Reaction of H_2O_2 and Bromide in pH 6.0 Phosphate Buffer. The general procedure was followed using **1-SePh** (0.201 g, 0.69 mmol, 2.8×10^{-2} M) as the catalyst. Aliquots were withdrawn over 4 h. The infinity point was obtained by allowing the reaction to stir at room temperature for 24 h, followed by GC analysis of the organic layer for the amounts of **1** and **2** present relative to diphenyl ether.

Kinetic Analysis of the 1-Se(=O)Ph-Catalyzed Reaction of H_2O_2 and Bromide in pH 6.0 Phosphate Buffer. The general method for

oxidation of **1-SePh** (0.209 g, 0.72 mmol) with NCS was followed to give **1-Se(=O)Ph** (0.220 g, 0.72 mmol). The general procedure for the kinetic analysis of catalyzed reactions of H_2O_2 and bromide in pH 6.0 phosphate buffer was followed using **1-Se(=O)Ph** (0.220 g, 0.72 mmol) as the catalyst. The infinity point was obtained by allowing the reaction to stir at room temperature for 24 h, followed by GC analysis of the organic layer for the amounts of brominated products **1** and **2** present.

A plot of $\ln(A_\infty - A_t)$, where A_∞ is the concentration of brominated products **1** and **2** at infinity and A_t is the concentration of brominated products **1** and **2** at time t , as a function of time is linear with the slope defined as $-k_{\text{OBS}}$. The values in Table 1 are the average of triplicate runs (\pm standard deviation).

Procedure for the Kinetic Analysis of the One-Phase Oxidation of Selenium Catalysts with *tert*-Butyl Hydroperoxide. Deuteriochloroform (0.8 mL), *tert*-butyl hydroperoxide (0.100 mL, 5.0 M in decane, 0.5 mmol, 0.55 M), and a selenide [**1-SePh** (0.0082 g, 0.028 mmol, 3.5×10^{-2} M), **3-SePh** (0.0084 g, 0.0093 mmol, 1.2×10^{-2} M), **6-SePh** (0.0087 g, 0.0047 mmol, 5.8×10^{-3} M), or **12-SePh** (0.0088 g, 0.0023 mmol, 2.9×10^{-3} M)] were placed in an NMR tube. The temperature of the NMR probe was set to 323.0 K, and ^1H NMR spectra were taken every 5 min for 110 min. Oxidation of the selenium catalysts was the rate-determining step in the process and was slow relative to selenoxide elimination. Therefore, the rate of the appearance of the olefinic allyloxy protons was identical to the rate of oxidation. The appearance of signals (500 MHz) at δ 6.02 (ddt, 1 H, $J = 5.0, 10.5, 16, 1\text{H}$), 5.38 (dq, 1 H, $J = 1.5, 17.5$ Hz), and 5.25 (dq, 1 H, $J = 1.5, 10.5$ Hz) was monitored as a function of time. The allylic protons appeared at δ 4.50 (dt, $J = 1.5, 5.5$ Hz). For **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph**, the aromatic protons of the 1,1,1-tris(4-hydroxyphenyl)ethyl core (500 MHz, δ 6.97 (d, 6 H, $J = 8.5$ Hz), 6.83 (d, 6 H, $J = 8.5$ Hz) were used as an internal standard for integration. For **1-Se(=O)Ph**, the three *para* and *meta* protons of the Se(=O)Ph ring and the five protons of the phenoxy ring [7.48–7.53 (m, 3 H), 7.26 (t, 2 H, $J = 8.0$ Hz), 6.94 (t, 1 H, $J = 7.5$ Hz), 6.84 (d, 2 H, $J = 8.5$ Hz)] were used as an eight-proton internal integration standard. A plot of $\ln(\text{INT}_\infty - \text{INT}_t)$, where INT_∞ is the integral of the olefinic protons at infinity and INT_t is the integral of the olefinic protons at time t , as a function of time is linear with the slope defined as $-k_{\text{OX}}(t\text{-BuOOH})$. The values in Table 1 are the average of duplicate runs.

Procedure for the Kinetic Analysis of the Two-Phase Oxidation of Selenium Catalysts with H_2O_2 . Deuterated chloroform (10 mL), 30% H_2O_2 (6.25 mL, 55 mmol, 3.4 M), pH 6.0 phosphate buffer (10 mL), NaBr, if used (3.32 g, 32 mmol, 2.0 M), and **1-SePh** (0.015 g, 0.052 mmol, 5.2×10^{-3} M), **3-SePh** (0.037 g, 0.041 mmol, 4.1×10^{-3} M), **6-SePh** (0.035 g, 0.019 mmol, 1.9×10^{-3} M), or **12-SePh** (0.037 g, 0.0097 mmol, 9.7×10^{-4} M) were combined and stirred at 296 K for 100 min, or until oxidation was complete. Aliquots of the CDCl_3 phase (<0.5 mL) were placed in an NMR tube, and CDCl_3 was added to give a volume of 1.0 mL. Samples were then placed in a CO_2 /acetone bath until ^1H NMR spectra were acquired. The percentage of oxidation was determined by integration of the *ortho* protons of Se(=O)Ph [500 MHz δ 7.70 (dd, $J = 1.5, 8.0$ Hz)] vs the 12 aromatic protons of the 1,1,1-tris(4-hydroxyphenyl)ethyl core (500 MHz, δ 6.97 (d, 6 H, $J = 8.5$ Hz), 6.83 (d, 6 H, $J = 8.5$ Hz) for **3-SePh**, **6-SePh**, and **12-SePh**, or, for **1-SePh**, the 3 *para* and *meta* protons of the Se(=O)Ph ring and the 5 protons of the phenoxy ring [7.48–7.53 (m, 3 H), 7.26 (t, 2 H, $J = 8.0$ Hz), 6.94 (t, 1 H, $J = 7.5$ Hz), 6.84 (d, 2 H, $J = 8.5$ Hz)].

An infinity point was taken after 24 h at 323 K. A plot of $\ln(\text{INT}_\infty - \text{INT}_t)$, where INT_∞ is the integral of the olefinic protons at infinity and INT_t is the integral of the olefinic protons at time t , as a function of time is linear with the slope defined as $-k_{\text{OX}}(\text{H}_2\text{O}_2)$. The values in Table 1 are the average of duplicate runs.

Procedure for Determining the Rate of Elimination of Phenylselenenic Acid from Selenoxide Catalysts. The selenoxide catalyst

was prepared by either of the oxidation procedures described above, taken up in CDCl_3 , and placed in a capped NMR tube. The temperature of the NMR probe was set to 323 K, and a ^1H NMR spectrum was taken every 5 min for 110 min. The appearance of the olefinic allyloxy protons (500 MHz) at δ 6.02 (ddt, 1 H, $J = 5.0, 10.5, 16$ Hz, 1H), 5.38 (dq, 1 H, $J = 1.5, 17.5$ Hz), and 5.25 (dq, 1 H, $J = 1.5, 10.5$ Hz) was monitored as a function of time. The allylic protons appeared as a new signal at δ 4.50 (dt, $J = 1.5, 5.5$ Hz). For **3-Se(=O)Ph**, **6-Se(=O)Ph**, and **12-Se(=O)Ph**, the aromatic protons of the 1,1,1-tris(4-hydroxyphenyl)ethyl core (500 MHz, δ 6.97 (d, 6 H, $J = 8.5$ Hz), 6.83 (d, 6 H, $J = 8.5$ Hz) were used as an internal standard for integration. For **1-Se(=O)Ph**, the entire aromatic region (500 MHz, δ 7.72–6.83) was used as a 10-proton internal integration standard.

An infinity point was taken after 24 h at 323 K. A plot of $\ln(\text{INT}_\infty - \text{INT}_t)$, where INT_∞ is the integral of the olefinic protons at infinity and INT_t is the integral of the olefinic protons at time t , as a function of time is linear with the slope defined as $-k_{\text{ELIM}}$. The values in Table 1 are the average of duplicate runs.

Procedure for the Attempted Bromination of Cyclohexene with 3-Se(=O)Ph and NaBr. Oxidation of **3-SePh** (0.45 g, 0.50 mmol) with *N*-chlorosuccinimide (2.315 g, 17.3 mmol, 45.0 equiv) in 30 mL of 1/1 $\text{CH}_3\text{OH}/\text{CH}_2\text{Cl}_2$ according to the procedure described above gave **3-Se(=O)Ph** (0.45 g, 0.48 mmol, 96%). Cyclohexene (0.21 mL, 2.0 mmol), **3-Se(=O)Ph** (0.45 g, 0.48 mmol), and NaBr (1.05 g, 10.2 mmol, 2 M) in a two-phase mixture of pH 6.0 phosphate buffer (5 mL) and CH_2Cl_2 (5 mL) were stirred at room temperature for 24 h. The organic phase was analyzed for *trans*-1,2-dibromocyclohexane (**1**) and *trans*-2-bromocyclohexanol (**2**) both by ^1H NMR and by gas chromatography. Neither **1** nor **2** was detected by either method.

Stopped-Flow Experiments. All stopped-flow experiments were performed on an SX18 stopped-flow spectrometer (Applied Photophysics, Leatherhead, U.K.). The sample-handling unit was fitted with two drive syringes that are mounted inside a thermostated bath

compartment, which allowed for variable-temperature experimentation. The optical detection cell was set up in the 2 mm path length. First- and second-order curve fitting and rate constants used a Marquardt algorithm¹⁹ based on the routine Curfit.²⁰

Oxidation of 1-TePh and 1-SePh. Stock solutions of 2.06×10^{-3} M **1-TePh** or **1-SePh** and 2.06×10^{-2} M H_2O_2 in MeOH were prepared. These two solutions were mixed in the stopped-flow spectrometer to give concentrations of 1.03×10^{-3} M telluride and 1.03×10^{-2} M H_2O_2 , and the increase in absorbance at 352 nm for **1-TePh** or **1-SePh** was measured as a function of time for 7–10 independent runs (\pm standard deviation). A plot of $\ln(A_\infty - A_t)$, where A_∞ is the concentration of **1-Te(=O)Ph** or **1-Se(=O)Ph** at infinity and A_t is the concentration of **1-Te(=O)Ph** or **1-Se(=O)Ph** at time t , as a function of time is linear with the slope defined as $-k_{\text{OBS}}$. The second-order rate constant, $k_{\text{OX}}(\text{H}_2\text{O}_2)$ was calculated by dividing k_{OBS} by the H_2O_2 concentration (1.03×10^{-2} M).

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Supporting Information Available: ^1H NMR and mass spectra for **1-Se(=O)Ph**, **3-Se(=O)Ph**, and **6-Se(=O)Ph**, ^1H NMR spectrum for **12-Se(=O)Ph**, and typical ^1H NMR traces for selenoxide elimination. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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