The Tris(trimethylsilyl)silane/Thiol Reducing System: A Tool for Measuring Rate Constants for Reactions of Carbon-Centered Radicals with Thiols

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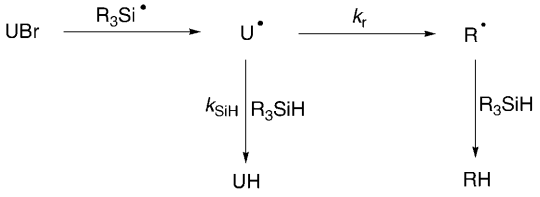
Dedicated to the memory of Professor *Hanns Fischer*, a pioneer in radical chemistry

An extension of the well-known 'free-radical-clock' methodology is described that allows one to determine the rate constants of carbon-centered radicals with a variety of thiols by using the tris(trimethylsilyl)silane/thiol couple as a reducing system. A total of 20 rate constants for the hydrogen abstraction from a variety of alkyl-, silyl-, and aryl-substituted thiols by the primary-alkyl radical **2** in toluene at 80° were determined with the aid of the 5-*exo-trig* cyclization as a timing device. Further, seven rate constants for the hydrogen abstraction from a variety of alkyl- and silyl-substituted thiols by the acyl radical **9** in benzene at 80° were measured using the decarbonylation process as a timing device. The rate constants varied over two orders of magnitude from 10^6 to 10^8 M^{-1} s^{-1}. Substituent effects were rationalized. The radical-trapping abilities of these reducing systems and those of other common hydrogen donors were compared.

Introduction. – One of the most-important reactions in free-radical chemistry is hydrogen abstraction from thiols by carbon-centered radicals. Glutathione, which has typical intracellular concentrations of a few millimol per liter, is considered a major participant in the 'repair' reaction of carbon-centered radicals produced in biological systems [1]. Kinetics data on the reactions of thiols with alkyl radicals are numerous and were measured by competitive or time-resolved spectroscopy [2–10]. A variety of substituted alkyl radicals were employed in organic, aqueous, and mixed solutions. For example, primary-, secondary-, or tertiary-alkyl radicals abstract hydrogen from $\text{Me(CH}_2)_7\text{SH}$ [4][5] and PhSH [6][7], with rate constants of *ca.* 10^7 and 10^8 M^{-1} s^{-1}, respectively, in organic solvents. An alkoxy (OR) or hydroxy (OH) group as an individual substituent in α- or β-position from the radical center has also no net kinetic effects on the thiol trapping [4]. A small accelerating effect is observed when the reactions are run in aqueous solutions [8]. Interestingly, all the rate constants were found to be essentially the same for a specific thiol, despite the change of the reaction thermochemistry. Two peculiarities on the radical substituents are found: *i*) the α,β-dimethoxy-substituted carbon-centered radical reacts with octanethiol about ten times slower than the unsubstituted analogues [4], and *ii*) the rate constants for the reaction of the α-hydroxyalkyl radical with a variety of water-soluble alkanethiols were found to be in the order $\text{HO(Me}_2)\text{C}^{\bullet} > \text{HO(Me)CH}^{\bullet} > \text{HOCH}_2^{\bullet}$, the former reacting about five times faster than the latter [3][9][1]). The observed trends were rationalized in terms of enthalpic and polar effects [4][9][10]. The dissociation enthalpy of MeS–H is 87.4 ± 0.6 kcal/mol, and is independent from the alkyl moiety (R = Me, Et, Pr, *etc.*) attached to the S-atom [11]. The dissociation enthalpy of PhS–H is 78.9 ± 1.4 kcal/mol and varies from 71.0 to 81.5 kcal/mol when changing the *para* substituent [11]. Interestingly, very little is known about the influence of R or Ar in aliphatic or aromatic thiols (RSH or ArSH, resp.) on the reactivity towards alkyl radicals. For example, primary- or tertiary-alkyl radicals react with *t*-BuSH three times slower than with $Me(CH_2)_7SH$ [4][5][7]. In aqueous solution, methyl and 2′-deoxyuridin-1′-yl radicals react with glutathione two times faster than with ethanethiol or 2-mercaptoethanol (= 2-sulfanylethanol), respectively [8][12].

More than two decades ago, *Griller* and *Ingold* [13] introduced the so-called 'free-radical-clock' methodology for measuring rate constants of radical reactions. The method became very popular since no special instrumentation is required and simple operations are carried out that can be applied in any laboratory [14]. Our group has successfully applied this method to measure several hundreds of rate constants mainly involving hydrogen abstraction from Group-14 hydrides by alkyl radicals [15][16]. How the methodology works is shown in *Scheme 1*. For example, the ratio of unrearranged (UH) to rearranged (RH) products formed in the radical chain reaction between a bromide (UBr) and a silane (R_3SiH) of known concentration under pseudo-first-order conditions allows the ratio k_r/k_{SiH} to be determined experimentally. A necessary condition is that the radical $U^\bullet$ is partitioned between the two reaction channels, *i.e.*, a reaction with R_3SiH and rearrangement to $R^\bullet$. The rate constant, k_{SiH}, can then be obtained providing that k_r has been previously determined.

Scheme 1. *'Free-Radical-Clock' Methodology and the Kinetics Expression Associated with Pseudo-First-Order Conditions*



$$\frac{[UH]}{[RH]} = \frac{k_{SiH}}{k_r}[R_3SiH]_0$$

Although thiols are rather good hydrogen donors, they cannot give this scenario since thiyl radicals are very poor abstracting agents and, therefore, do not support chain reactions analogous to *Scheme 1*. Recently, *Roberts* [17] reported that trialkylsi-

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[1]) A number of rate constants for the reaction of α-hydroxyalkyl radicals with a variety of water-soluble thiols have been obtained by indirect methods using pulse radiolysis [3]. Some of these values, particularly those obtained at higher pH, may be a few times faster than those obtained by other techniques. The uncertainties that could be involved with these methods have been discussed [2c].

lanes reduce alkyl halides to the corresponding hydrocarbons in the presence of alkanethiols. Thereby, the key step in these reductions is hydrogen transfer from the silane to the thiyl radical, a process that is strongly endothermic and reversible. The rate constants k_{SH} and k_{SiH} for the reaction of, *e.g.*, the adamantane-1-thiyl radical (1-AdS$^•$) with $\mathrm{Et_3SiH}$ (*Eqn. 1*) are found to be 3.2×10^4 and 5×10^7 $\mathrm{M^{-1}\,s^{-1}}$, respectively, at 60° [18]. The forward rate constant is relatively fast, taking into consideration the endothermicity of this reaction ($\Delta H_r = +7.6$ kcal/mol)[2]).

$$\text{1-AdS}^{\bullet} + \mathrm{Et_3SiH} \underset{k_{\mathrm{SiH}}}{\overset{k_{\mathrm{SH}}}{\rightleftharpoons}} \text{1-AdSH} + \mathrm{Et_3Si}^{\bullet} \tag{1}$$

The reactions of alkanethiyl (RS$^•$) and benzenethiyl (PhS$^•$) radicals with $\mathrm{(TMS)_3SiH}$ ($\mathrm{TMS = Me_3Si}$) [19] are also known (*Eqns. 2* and *3*). Thiols have shown to catalyze the addition of $\mathrm{(TMS)_3SiH}$ to ketones and alkenes, where *Eqn. 2* is suggested to play an important role [20]. The process of *Eqn. 3* is also suggested as key step in the reaction of unsubstituted and 2-substituted allyl phenyl sulfides with $\mathrm{(TMS)_3SiH}$, which provides the corresponding allyl tris(trimethylsilyl)silanes in excellent yields [21]. However, the currently known bond-dissociation energies [11][16] of the S−H and Si−H bond in thiols and silanes, respectively, suggest that the process of *Eqn. 3* is endothermic by 5.0 kcal/mol, whereas that of *Eqn. 2* is expected to be exothermic by −3.5 kcal/mol. The above considerations suggest that RSH/$\mathrm{(TMS)_3SiH}$, and to a lesser extent ArSH/$\mathrm{(TMS)_3SiH}$, should be good reduction systems under controlled conditions where the hydrogen donor is the thiol. Herein, we describe an extension of the 'free-radical-clock' methodology [13][14] that allows one to determine rate constants of carbon-centered radicals with a variety of thiols.

$$\mathrm{RS^{\bullet} + (TMS)_3SiH \rightleftharpoons RSH + (TMS)_3Si^{\bullet}} \tag{2}$$

$$\mathrm{PhS^{\bullet} + (TMS)_3SiH \rightleftharpoons PhSH + (TMS)_3Si^{\bullet}} \tag{3}$$

Results and Discussion. – Bromide **1** was chosen as the precursor of carbon-centered radicals because: *i*) *Beckwith* and *Glover* [22] studied the kinetics of the cyclization **2** → **3** by ESR spectroscopy, *Arrhenius* parameters being available; *ii*) the absolute rate constant for the reaction of $\mathrm{RCH_2CH(OMe)CH_2^{\bullet}}$ with octanethiol is known [4]; and *iii*) the rate constant for the cyclization is in the appropriate range for competition reactions with thiols. Therefore, we could carefully check the validity of our kinetics approach. *Scheme 2* shows the expected underlying mechanism, and *Eqn. 4* represents the kinetics expression associated with this mechanistic scheme under pseudo-first-order conditions.

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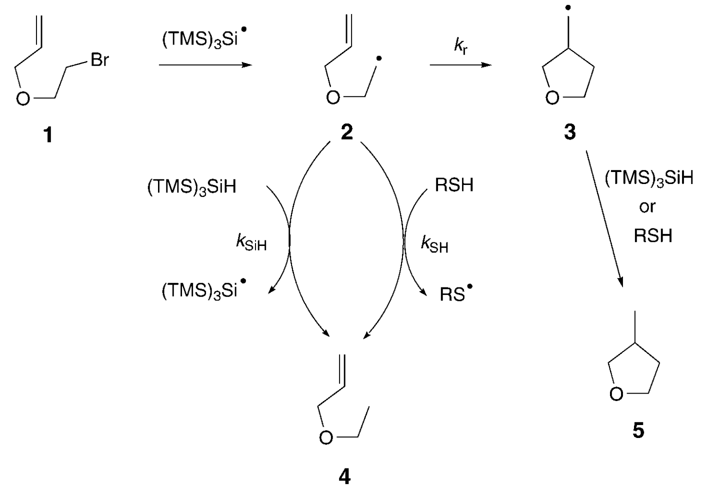
[2]) The equilibrium constant $K = k_{\mathrm{SH}}/k_{\mathrm{SiH}}$ is 6.2×10^{-4} and, hence, $\Delta G_r = +4.9$ kcal/mol. Unfortunately, ΔS_r is unknown, which would have allowed to determine ΔH_r, *i.e.*, the difference in bond-dissociation enthalpy of the corresponding silane and thiol in solution. The difference of the simpler silane and thiol, $\Delta H(\mathrm{Me_3Si{-}H})$ and $\Delta H(\mathrm{MeS{-}H})$, in the gas phase corresponds to $\Delta H_r = +7.6$ kcal/mol [11][16].

Scheme 2. *Radical Chain Reduction of* **1** *by the (TMS)$_3$SiH/Thiol Reducing System*



$$\frac{[\mathbf{4}]}{[\mathbf{5}]} = \frac{k_{\mathrm{SiH}}}{k_{\mathrm{r}}}[(\mathrm{TMS})_3\mathrm{SiH}]_0 + \frac{k_{\mathrm{SH}}}{k_{\mathrm{r}}}[\mathrm{RSH}]_0 \qquad (4)$$

To determine the kinetics under pseudo-first-order conditions, a series of experiments were conducted in which bromide **1** was treated with a large excess of tris(trimethylsilyl)silane ((TMS)$_3$SiH) and RSH in known concentrations. The quantities of unrearranged **4** and rearranged **5** as the products were determined by GC analysis, following the thermally initiated (AIBN, 80°) radical reaction, and by using an internal standard. *Fig. 1* shows the linear regression analyses of the ratio [**4**]/[**5**] *vs.* [(TMS)$_3$SiH], by keeping constant the concentration of Me(CH$_2$)$_{11}$SH (237 mM; solid circles), and [**4**]/[**5**] *vs.* [Me(CH$_2$)$_{11}$SH], by keeping constant the concentration of (TMS)$_3$SiH (554 mM; open circles). The slopes of the two lines give $k_{\mathrm{SiH}}/k_{\mathrm{r}} = 0.08 \pm 0.02\ \mathrm{M}^{-1}$, and $k_{\mathrm{SH}}/k_{\mathrm{r}} = 0.87 \pm 0.06\ \mathrm{M}^{-1}$, respectively[3]). Kinetics data can also be obtained from the intercepts of the two lines in *Fig. 1*, based on *Eqn. 4*, although large errors are associated with these values. However, it was gratifying to find for these analyses $k_{\mathrm{SH}}/k_{\mathrm{r}} = 0.89 \pm 0.06\ \mathrm{M}^{-1}$ and $k_{\mathrm{SiH}}/k_{\mathrm{r}} = 0.32 \pm 0.97\ \mathrm{M}^{-1}$, respectively.

After demonstrating the appropriateness of our kinetics approach, we proceeded to study the reaction of radical **2** with a variety of alkanethiols to determine unknown rate constants. *Fig. 2* shows the linear-regression analyses obtained for '*tert*-dodecanethiol' (= mixture of isomers), octane-1-thiol, butane-1,4-dithiol, and 1,4-dithioerythritol (= (2*R*,3*S*)-1,4-disulfanylbutane-2,3-diol); and in *Table 1*, the reactivities toward radical **2** (in terms of $k_{\mathrm{SH}}/k_{\mathrm{r}}$ values) are summarized for eleven different thiols.

Cyclohexanethiol and *tert*-dodecanethiol (*Table 1*, *Entries 1* and *2*, resp.), which show the same reactivities, react two times slower than Me(CH$_2$)$_7$SH (*Entry 3*) or

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[3]) From $k_{\mathrm{SiH}}/k_{\mathrm{r}} = 0.08\ \mathrm{M}^{-1}$ and $k_{\mathrm{r}} = 2.6 \times 10^7\ \mathrm{s}^{-1}$ at 80° [22], a value of k_{SiH} of $2.1 \times 10^6\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$ is obtained. The k_{SiH} for the primary-alkyl radical RCH$_2$CH$_2$CH$_2^•$ with (TMS)$_3$SiH is $1.2 \times 10^6\ \mathrm{M}^{-1}\ \mathrm{s}^{-1}$ at the same temperature [30].

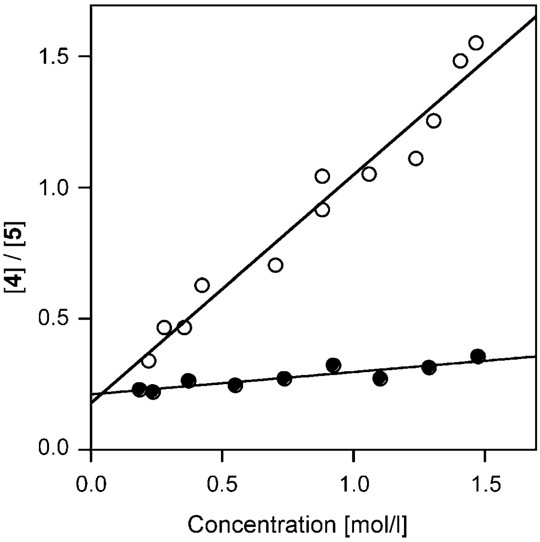


Fig. 1. *Plots of* [**4**]/[**5**] vs. *[Me(CH$_2$)$_{11}$SH]* (○; [(TMS)$_3$SiH] = 554 mM) *and* vs. *[(TMS)$_3$SiH]* (●; [Me(CH$_2$)$_{11}$SH] = 237 mM) *for the reaction of* **1** *with (TMS)$_3$SiH/Me(CH$_2$)$_{11}$SH at 80°*

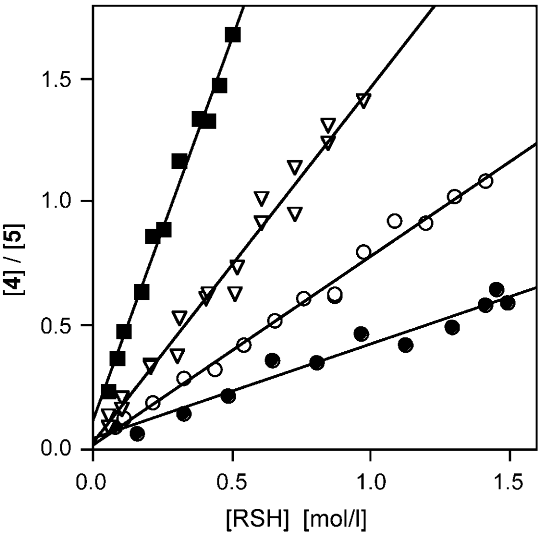


Fig. 2. *Plots of* [**4**]/[**5**] vs. *[RSH] for the reaction of* **1** *with (TMS)$_3$SiH/RSH at 80°.* [(TMS)$_3$SiH] ≈ 500 mM. Legend: *tert*-dodecanethiol (●), octanethiol (○), butane-1,4-dithiol (▽), 1,4-dithioerythritol (■).

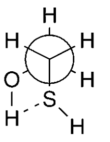
HO(CH$_2$)$_3$SH (*Entry 4*), presumably due to the higher steric hindrance. Similarly, PhCH$_2$SH (*Entry 7*) and Ph$_3$SiSH (*Entry 8*) show identical reactivities, and they react about two times faster than Me(CH$_2$)$_7$SH or HO(CH$_2$)$_3$SH. We suggest that the radicals PhCH$_2$S$^•$ and Ph$_3$SiS$^•$ are stabilized to a similar extent by two different effects, the former by a through-space interaction with the Ph ring, the latter by a direct interaction

Table 1. *Kinetics Data for the Reaction of Alkyl Radical* **2** *with a Variety of Alkanethiols.* In toluene at 80°; errors represent one standard deviation.

Entry	Thiol	k_{SH}/k_r [M^{-1}]	Intercept
1	$C_6H_{11}SH$	0.35 ± 0.04	0.09 ± 0.04
2	$C_{12}H_{25}SH$[a])	0.39 ± 0.03	0.04 ± 0.03
3	$Me(CH_2)_7SH$	0.76 ± 0.03	0.02 ± 0.02
4	$HO(CH_2)_3SH$	0.76 ± 0.01	0.10 ± 0.01
5	$Me(CH_2)_{11}SH$	0.87 ± 0.06	0.17 ± 0.53
6	$HO(CH_2)_2SH$	1.15 ± 0.08	0.07 ± 0.06
7	$PhCH_2SH$	1.32 ± 0.04	0.01 ± 0.04
8	Ph_3SiSH	1.32 ± 0.07	0.08 ± 0.02
9	$HS(CH_2)_4SH$	1.44 ± 0.05	0.03 ± 0.03
10	1,4-Dithiothreitol	2.70 ± 0.19	0.12 ± 0.06
11	1,4-Dithioerythritol	3.10 ± 0.12	0.11 ± 0.04

[a]) '*tert*-Dodecanethiol' (= mixture of isomers).

with the α-Si-atom. $HS(CH_2)_4SH$ (*Entry 9*) is found to react twice as fast than $Me(CH_2)_7SH$ or $HO(CH_2)_3SH$, as expected for statistical reasons. *Table 1* also shows that dithioerythritol (*Entry 11*) and dithiothreitol (=(2*S*,3*S*)-1,4-disulfanylbutane-2,3-diol; *Entry 10*), which have the same reactivity, react two times faster with radical **2** than $HS(CH_2)_4SH$, and that $HO(CH_2)_2SH$ is also more reactive than $HO(CH_2)_3SH$. These above thiols have in common the presence of an OH group in β-position to the S-atom. *Sung* and *Harmony* [23] showed by microwave spectroscopy that 2-mercaptoethanol adopts a preferred conformation like **6**, the barrier of rotation being *ca.* 1 kcal/mol. Therefore, we suggest that the intramolecular H-bonding or 'β-hydroxy effect', which is expected to be double for dithioerythritol (**7**) and dithiothreitol, participates in weakening the S–H bond, thus increasing the rate constants for hydrogen abstraction.



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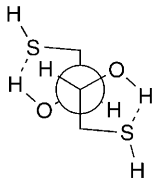

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The *Arrhenius* parameters for the reaction of primary-alkyl radicals with *t*-BuSH are log $A = 8.15 \pm 0.18$ (A in units of M^{-1} s^{-1}), with $E_a = 1.86 \pm 0.23$ kcal/mol, which leads to $k_{SH} = 1 \times 10^7$ M^{-1} s^{-1} at 80° [7]. The *Arrhenius* parameters for the cyclization step $\mathbf{2} \rightarrow \mathbf{3}$ are $\log A = 9.89 \pm 0.44$ (A in s^{-1}), with $E_a = 4.00 \pm 0.51$ kcal/mol, and $k_r = 2.6 \times 10^7$ s^{-1} at 80° [22]. Therefore, $k_{SH}/k_r = 0.39$ M^{-1} at 80°, which is identical to the value obtained in this study for *tert*-dodecanethiol (*Table 1*). Therefore, the k_{SH} values can be estimated with a certain accuracy from the data of *Table 1* and vary nearly by one order of magnitude at 80° when going from cyclohexanethiol to 1,4-dithioerythritol[4]).

Next, analogous experiments were performed with aryl- instead of alkyl-substituted thiols (*Scheme 2*). A variety of *para*- or *meta*-substituted benzenethiols were used, and these reactions behaved as expected. *Fig. 3* shows an example of the linear-regression analysis of the ratio [**4**]/[**5**] *vs.* the concentration of 3-clorobenzenethiol, by keeping constant the concentration of $(TMS)_3SiH$ (523 mM). The slope of the line gave $k_{SH}/k_r = 3.78 \pm 0.10$ M^{-1}, and the intercept was close to zero. *Table 2* summarizes the k_{SH}/k_r values obtained for a total of nine thiols.

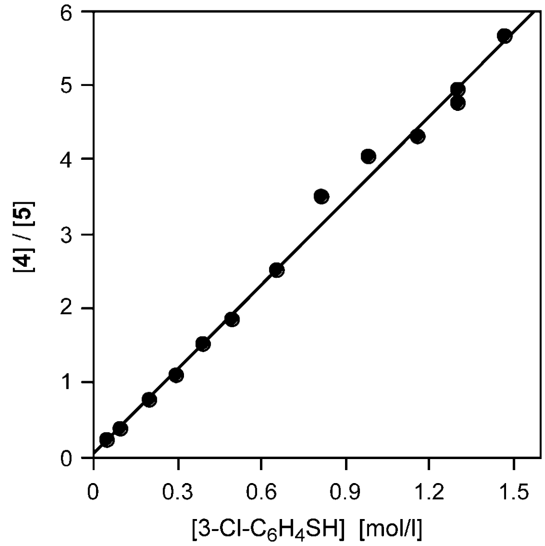

Fig. 3. *Plot of* [**4**]/[**5**] vs. *[3-Cl-C_6H_4SH] for the reaction of* **1** *with $(TMS)_3SiH$/3-Cl-C_6H_4SH at 80°.* $[(TMS)_3SiH] = 523$ mM.

In *Table 2*, the absolute rate constants for hydrogen abstraction (k_{SH}) are also reported, calculated from $k_r = 2.6 \times 10^7$ s^{-1} (at 80°) for the cyclization **2** → **3** [22]. A similar k_{SH} value for the reaction of radical **2** with PhSH can also be estimated from *Newcomb*'s work. From the *Arrhenius* parameters of the reaction $RCH_2CH_2CH_2^{\bullet}$ with PhSH, a k_{SH} of 1.5×10^8 M^{-1} s^{-1} (at 80°) can be calculated [7], whereas the β-MeO-substituted radical, *i.e.*, $RCH_2CH(OMe)CH_2^{\bullet}$, reacts two times slower than $RCH_2CH_2CH_2^{\bullet}$ with octanethiol at 30° [4].

All the relative rate constants are between 2.9 and 5.3, *i.e.*, the rate constants for hydrogen abstraction vary less than by a factor of 2 within the whole series. However, any attempt to correlate the observed reactivity for ArSH with the S–H bond-dissoci-

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[4]) To investigate the effect of solvent polarity, toluene, which has a dielectric constant ε of 2.379, was replaced by benzonitrile ($\varepsilon = 25.20$) or decan-1-ol ($\varepsilon = 1.983$) in the reaction of dodecane-1-thiol with radical **2**. Then, k_{SH}/k_r values of 1.21, 0.87, and 0.63 M^{-1} were obtained for benzonitrile, toluene, and decan-1-ol, resp. Although the changes are small, they indicate that the rate constants increase with increasing solvent polarity.

Table 2. *Kinetics Data for the Reaction of Alkyl Radical* **2** *with a Variety of Arenethiols.* In toluene at 80°; errors represent one standard deviation.

Thiol	k_{SH}/k_r [M^{-1}]	k_{SH} [M^{-1} s^{-1}]
C_6H_5SH	2.91 ± 0.07	7.6×10^7
4-Me-C_6H_4SH	2.87 ± 0.07	7.5×10^7
4-MeO-C_6H_4SH	3.96 ± 0.12	1.0×10^8
4-Cl-C_6H_4SH	4.12 ± 0.07	1.1×10^8
4-F-C_6H_4SH	5.29 ± 0.21	1.4×10^8
3-CF_3-C_6H_4SH	3.92 ± 0.30	1.0×10^8
3-Cl-C_6H_4SH	3.78 ± 0.10	9.8×10^7
3-F-C_6H_4SH	4.55 ± 0.12	1.2×10^8
Naphthalene-2-thiol	2.98 ± 0.11	7.7×10^7

ation energies (BDEs) or *Hammett* constants (σ or σ^+) did not give any fit [24]. It is worth pointing out that, *e.g.*, both 4-Cl and 4-MeO substituents enhance the reactivity, although there is 2.0 kcal/mol difference in BDE [11], and 0.50 kcal/mol difference in the σ scale (or 0.89 in the σ^+ scale) [25].

The hydrogen-donor abilities of the $(TMS)_3SiH$/thiol system is worth a further comment. *Fig. 4* reports rate constants for hydrogen abstraction from a variety of reducing systems by primary-alkyl radicals at 80°. The upper part of the diagram shows that primary-alkyl radicals abstract a H-atom from $(EtO)_2P(O)H$, Bu_3GeH, Bu_3SnH, and $(TMS)_3GeH$, with rate constants of 1.2×10^5, 3.8×10^5 , 6.4×10^6, and 1.5×10^7 M^{-1} s^{-1}, respectively, at 80° [26–28]. In the lower part of the figure, the reactivities of a few organosilanes and $(TMS)_3SiH$/thiols are reported. The rate constants cover a few orders of magnitude and indicate how the hydrogen-donor abilities of the reducing system can be modulated. Primary-alkyl radicals abstract a H-atom from $(TMS)_2Si(H)Me$, $(MeS)_3SiH$, and $(TMS)_3SiH$, with rate constants of 1.5×10^5, 3.9×10^5, and 1.2×10^6 M^{-1} s^{-1}, respectively [26] [29] [30], whereas the values for the $(TMS)_3SiH$/RSH and $(TMS)_3$-SiH/ArSH systems are in the range of $0.9 - 8 \times 10^7$ and $7.5 - 1.5 \times 10^8$ M^{-1} s^{-1}, respectively.

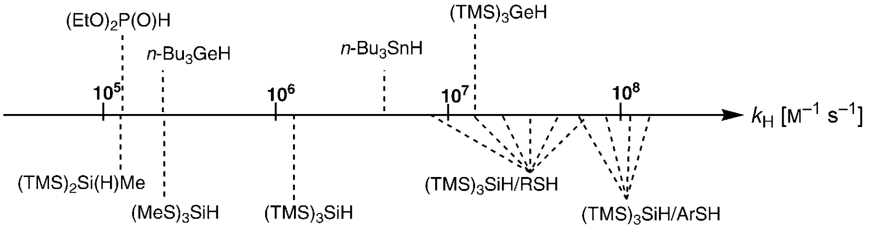
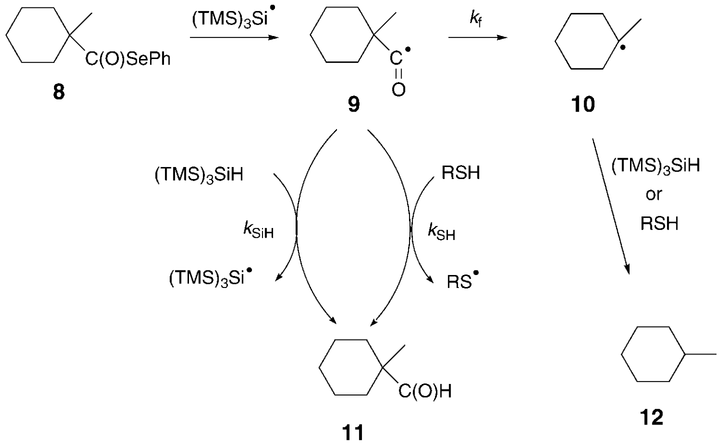


Fig. 4. *Rate constants for hydrogen abstraction from a variety of reducing systems by primary-alkyl radicals at 80°*

This new extension of the 'free-radical-clock' methodology can be, in principle, applied by using any radical rearrangement or fragmentation as a timing device. Obviously, the reactivity of $(TMS)_3SiH$ in these reactions plays a crucial role. We extended this approach for obtaining rate constants for the reaction of acyl radicals with thiols, an important step in many syntheses, and a process about which very little is known from a quantitative point of view [31]. The tertiary-substituted acyl selenide **8** was chosen as a precursor of acyl radicals because the kinetics of the decarbonylation **9** → **10** are available [31] [32], and since the rate constant lies in the appropriate range for competition reactions with thiols [33]. *Scheme 3* shows the expected mechanism. Also in this case, *Eqn. 4*, where [**4**]/[**5**] is replaced by [**11**]/[**12**], represents the kinetics expression associated with the proposed mechanism under pseudo-first-order conditions.

Scheme 3. *Radical Chain Reduction of* **8** *by the (TMS)$_3$SiH/Thiol Reducing System*



Selenide **8** was treated with 0.5M (TMS)$_3$SiH and RSH in known concentrations at 80°, using AIBN as the radical initiator. The quantities of the resulting unrearranged **11** and rearranged **12** were determined by GC analysis by using an internal standard. *Fig. 5* shows the linear-regression analyses of the ratio [**11**]/[**12**] *vs.* [RSH] for three substrates: octanethiol, butane-1,4-dithiol, and 1,4-dithioerythritol; and *Table 3* summarizes the k_{SH}/k_f values obtained for a total of seven thiols.

Table 3. *Kinetics Data for the Reaction of Acyl Radical* **9** *with a Variety of Alkanethiols.* In benzene at 80°; errors represent one standard deviation.

Thiol	k_{SH}/k_f [M^{-1}]	k_{SH} [M^{-1} s^{-1}]
$C_{12}H_{25}SH$[a])	0.24 ± 0.02	1.9×10^6
$HO(CH_2)_2SH$	0.83 ± 0.05	6.7×10^6
$Me(CH_2)_7SH$	0.92 ± 0.04	7.5×10^6
$HO(CH_2)_3SH$	1.17 ± 0.04	9.5×10^6
$HS(CH_2)_4SH$	2.13 ± 0.13	1.7×10^7
Ph_3SiSH	2.87 ± 0.15	2.3×10^7
1,4-Dithioerythritol	3.84 ± 0.28	3.1×10^7

[a]) '*tert*-Dodecanethiol' (= mixture of isomers).

In *Table 3*, the absolute rate constants for hydrogen abstraction (k_{SH}) are also reported, calculated for $k_f = 8.1 \times 10^6$ s^{-1} at 80° for the decarbonylation **9** → **10** [32].

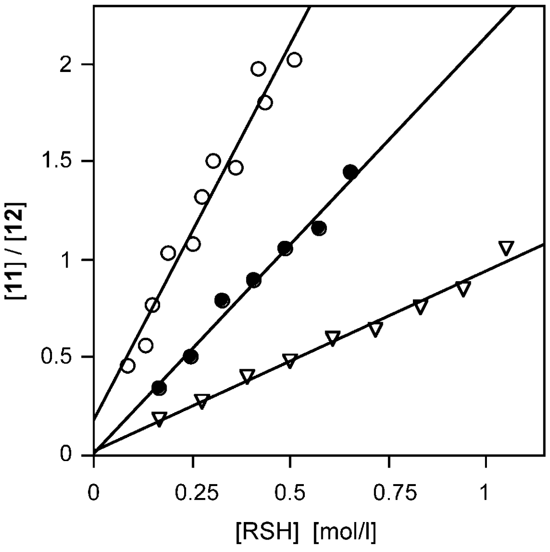


Fig. 5. *Plots of* [**11**]/[**12**] vs. *[RSH] for the reaction of* **8** *with (TMS)$_3$SiH/RSH at 80°.* [(TMS)$_3$SiH] ≈ 500 mM. Legend: Octanethiol (▽), butane-1,4-dithiol (●), 1,4-dithioerythritol (○).

The values vary from more than one order of magnitude from 1.9×10^6 (*tert*-dodecanethiol) to 3.1×10^7 M^{-1} s^{-1} (1,4-dithioerythritol). The former reacts about four times slower than Me(CH$_2$)$_7$SH or HO(CH$_2$)$_3$SH due to the higher steric hindrance. HS(CH$_2$)$_4$SH was found to react two times faster than Me(CH$_2$)$_7$SH or HO(CH$_2$)$_3$SH, as we found for the alkyl radical **2**. Ph$_3$SiSH reacts about three times faster than Me(CH$_2$)$_7$SH or HO(CH$_2$)$_3$SH due to the higher stabilization of the Ph$_3$SiS$^•$ radical. 1,4-Dithioerythritol reacts two times faster than HS(CH$_2$)$_4$SH, as we found for the analogous reactions of alkyl radical **2**, probably due to the intramolecularly H-bonded structure **7**, which weakens the S–H bond. For comparison, a rate constant of 1.8×10^7 M^{-1} s^{-1} at 25° was reported for the reaction of the benzoyl (PhC(O)$^•$) radical with PhSH [33].

Conclusions. – (TMS)$_3$SiH is known to be an efficient reducing agent under free-radical conditions [16][19]. In this paper, we have shown that (TMS)$_3$SiH in combination with thiols (RSH or ArSH) functions as a free-radical reducing system (*Schemes 2* and *3*). The role of the thiol is to modulate the hydrogen-donor ability of the couple and to allow the fast reaction of carbon-centered radicals with thiols to be studied. Indeed, the radical-trapping abilities of a variety of alkyl-, silyl-, and aryl-substituted thiols towards the primary-alkyl radical **2** or the acyl radical **9** are obtained by using the 'free-radical-clock' methodology. The determined rate constants vary over two orders of magnitude in the range 10^6–10^8 M^{-1} s^{-1}. The influence of the thiol substituent on the reactivity of primary-alkyl or acyl radicals was studied and rationalized. Steric effects and the *β*-hydroxy effect (probably through intramolecular H-bonds) play a major role in alkanethiols. Silyl-substituted thiols enhance appreciably the reactivity, too. Substituents in 3- or 4-position of benzenethiol have a very small effect, indicating that polar effects in these reactions are unimportant [34]. We are confident that the kinetics data reported in this work will find wide and general use in mechanistic and synthetic applications. For example, the effect of β-hydroxy substituents and the concept of enhancing reactivity through H-bonding are worth of further consideration in aqueous solution.

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Experimental Part

Toluene or benzene, containing a small amount of nonane, decane, or undecane as internal GC standards, were used as solvent. Samples containing *ca.* 0.5M of $(TMS)_3SiH$, the appropriate thiol, and bromide **1** (or selenide **8**), with a thiol/substrate ratio of $\geq 20:1$, were degassed in *Wheaton* reactors. Reactions were initiated with the aid of AIBN (=2,2′-azobis(isobutyronitrile)) at 80°. The products of interest were identified by comparison of their retention times with those of authentic materials.

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