Stereochemical Course of Free-Radical Additions of Mercaptans to *trans*-Δ^2-Octalin

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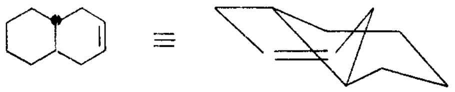
The light-induced additions of mercaptans to *trans*-Δ^2-octalin yielded a mixture of two isomeric sulfides, an axial 2-alkanethio-*trans*-decalin and an equatorial 2-alkanethio-*trans*-decalin. The axial isomer predominated over the equatorial isomer by a factor of about 8–12 to 1. Changing the initial concentrations of the reactants had no effect on the ratio of the products formed in these reactions. The stereochemical course of the addition of mercaptans is discussed in terms of the conformational factors encountered in the addition of a free radical to the double bond of a cyclohexene ring system.

Previous work has shown that the nature of the products obtained from the free-radical addition of mercaptans to a cyclohexene with a fixed conformation is determined by conformational factors encountered in the addition of a free radical to the double bond.[2] Thus, the addition of methyl mercaptan to 4-*t*-butylcyclohexene yielded a mixture of four isomeric sulfides, *cis*- and *trans*-4-*t*-butylcyclohexyl methyl sulfide and *cis*- and *trans*-3-*t*-butylcyclohexyl methyl sulfide. In these additions, the axially substituted isomers, *cis*-4-*t*-butylcyclohexyl methyl sulfide and *trans*-3-*t*-butylcyclohexyl methyl sulfide, predominated over the equatorially substituted isomers. The present work is concerned with the free-radical additions of mercaptans to *trans*-Δ^2-octalin (I), another system having a cyclohexene ring with a fixed conformation. This system presents an advantage over the 4-*t*-butylcyclohexene system in that only two isomeric products are formed in the addition reaction rather than four.



I

Results

The light-induced addition of methyl mercaptan to I yielded a mixture of two addition products, axial 2-methanethio-*trans*-decalin (II) and equatorial 2-methanethio-*trans*-decalin (III). Gas chromatographic analysis of the product mixture showed that one of the addition products predominated over the other by a factor of about 8. Samples of II and III were isolated by preparative gas chromatography and each sulfide was converted to its corresponding sulfone, IV and V. The sulfone of the predominant isomer (mp 119–120°) underwent isomerization to the sulfone of the minor isomer (mp 88°) when heated in ethanol with sodium ethoxide. Isomerization of a sulfone group from an axial position to an equatorial position is known to occur under these conditions.[3] Thus, it was established that the predominant isomer formed in the addition of methyl mercaptan to *trans*-Δ^2-octalin is II, the isomer with the methanethio group in the axial position. (See Scheme I.)

The relative amounts of the two isomers formed in this addition reaction were not influenced to any measurable extent by varying the ratio of methyl mercaptan and I in the reaction mixture. Table I shows that essentially the same product distribution is obtained over a range of mercaptan/olefin ratios of 45.

SCHEME I

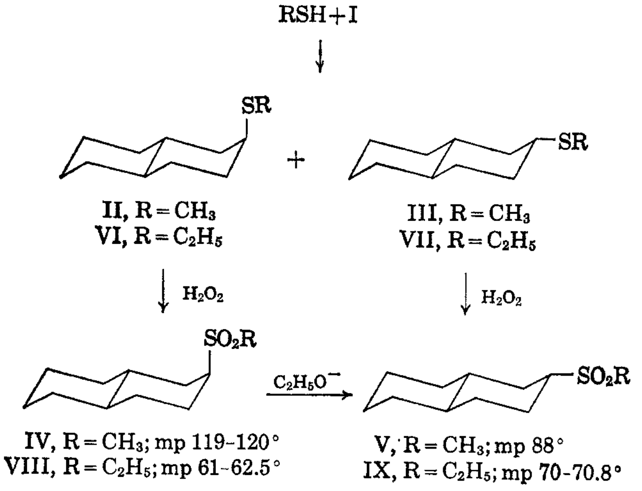


TABLE I

EFFECT OF MERCAPTAN/OLEFIN RATIO PRODUCT DISTRIBUTION

[CH_3SH]/[I]	% II	% III
9.1	91	9
6.2	87	13
3.6	90	10
2.2	87	13
0.63	88	12
0.26	89	11

Addition of ethyl mercaptan to I gave results essentially the same as those observed in the methyl mercaptan additions. The axial 2-ethanethio-*trans*-decalin (VI) predominated over the equatorial 2-ethanethio-*trans*-decalin (VII) by a factor of about 12 to 1, and varying the concentrations of the reactants had no detectable effect on the relative amounts of the two isomers formed in the reactions. In one experiment, the ethyl mercaptan was added dropwise to the illuminated *trans*-Δ^2-octalin in order to maintain a very high olefin-to-mercaptan ratio. The composition of the product mixture was the same as that found for a reaction where the olefin was added dropwise to the illuminated mercaptan, a situation in which a very high ratio of mercaptan to olefin was maintained. Identification of the isomeric sulfides was accomplished by conversion of the mixture of sulfides to a mixture of the sulfones which on recrystallization gave a 77% yield of a sulfone that melted at 61–62°.

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(2) E. S. Huyser and J. R. Jeffrey, *Tetrahedron*, **21**, 3083 (1965).

(3) E. L. Eliel and B. P. Thill, *Chem. Ind.* (London), **88** (1963).

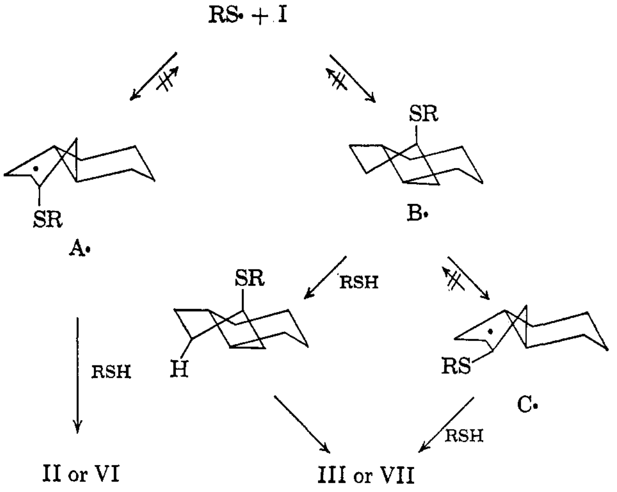
Heating this sulfone in alcoholic sodium ethoxide yielded an isomeric sulfone that melted at 70.5°. Thus, the major sulfone obtained from the sulfide mixture was the axial isomer (VIII) which could be epimerized by treatment with base to the equatorial isomer (IX).

Discussion

Since the additions of mercaptans to I yield mixtures in which the axial, and presumably less stable, isomer predominates, it appears that the stereochemical course of the reaction is determined by kinetic aspects of the reaction rather than by thermodynamic equilibration of the reaction products. The mercaptan adds to the alkene in a free-radical chain reaction consisting of addition of an alkanethiyl radical (RS·) to the unsaturated linkage yielding an adduct radical which abstracts a hydrogen atom from the mercaptan. The stereochemistry of this addition must be determined in the addition of RS· to the alkene since it is immaterial whether the elements of the mercaptan add *cis* or *trans* to the double bond. Although the 2 and 3 carbons of I are equivalent, the approach to these carbons is not. Examination of the conformational picture of I shows that approach by the adding thiyl radical to the 2 carbon from below and to the 3 carbon from above will be *cis* to the 8- and 5-methylenes of the other ring, respectively, and yield the same adduct radical, A·. Approach by the adding thiyl radical to the 2 carbon from above and to the 3 carbon from below will be *trans* to the 8- and 5-methylenes of the other ring and yield the same adduct radical, B·. The conformations of radicals A· and B· differ in that A· has a chair conformation and B· has a skew-boat conformation. Since the skew-boat conformation of cyclohexane is less stable than the chair conformation to the extent of about 5.5 kcal/mole,[4] the formation of the adduct radical B· which has this conformation might well be expected to be slower than the rate of formation of A·. Radical A· on reaction with the mercaptan yields an axially substituted sulfide. The twist-boat adduct radical B· may react with mercaptan to yield a sulfide which, on isomerization to the chair conformer, is the equatorially substituted isomer. However, more likely the adduct radical B· isomerizes to C·, an adduct radical with the thio group in the equatorial position, and reaction of C· with the mercaptan yields the equatorially substituted sulfide. (See Scheme II.)

Thiyl radical additions to alkenes are reversible reactions. Our purpose in studying the effect of mercaptan concentration on the ratio of products was to determine if the reversibility of the addition reaction had any effect on the product distribution. Previous work has shown that the ease of elimination of a thiyl radical is dependent on the stability of the adduct radical relative to the stability of the unsaturated compound to which the addition occurs.[5] Thus, elimination of RS· will be fast if the unsaturated compound to which the addition is taking place is relatively free of bond-angle deformation or conformational strain and the adduct radical is comparatively unstable because of strain owing to a severe conformation problem. Conversely, elimination of RS· from an adduct radical that is relatively free of conformational strain compared to the unsaturated compound would be less facile. Indeed, if the elimination from an adduct radical free of conformational strain yielded an unsaturated compound that was subjected to greater strain than the adduct radical itself, the elimination of RS· might be very slow. The situation encountered in the formation of the conformationally strained adduct radical B· and the adduct radical A· which is relatively free of conformational strain suggests that B· should undergo elimination of RS· faster than A·.

SCHEME II



If the rates of elimination of RS· from the adduct radicals are similar to those of the reactions of the adduct radicals with mercaptan yielding the addition products, or, in the case of B· the rate of isomerization to C·, the distribution of the products would be dependent on the mercaptan concentration. The reactions of the conformationally strained radical B· yielding the equatorially substituted product would be faster at high concentrations of mercaptan, and one might expect increasing the mercaptan/olefin ratio would change the product distribution in favor of the equatorially substituted product. A plausible explanation for the lack of this concentration effect in this system is that the adduct radical B· isomerizes to the chair conformer C· faster than it undergoes elimination. Once in the chair conformer C·, the thiyl group is in an equatorial position and is not capable of being eliminated unless the radical isomerizes back to the less stable twist-boat conformer. Thus, the consequence of the formation of B· is that the thiyl radical is trapped and is not capable of elimination.

However, elimination of RS· from A· should still be possible. If it is assumed now that elimination can occur from this radical and not from B·, increasing the mercaptan concentration might be expected to increase the amount of the axially substituted sulfide relative to the equatorial isomer. The fact that this effect was not observed suggests that elimination of RS· from A· is also much slower than reaction of A· with mercaptan to yield the axial sulfide. Such would be the case if the adduct radical is subjected to less bond-angle deformation than the alkene. This may well be the case. A careful vector analysis of alicyclic rings by Corey and Sneen[6] showed that both rings of

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(4) W. S. Johnson, J. L. Margrave, V. J. Bauer, M. A. Frish, H. L. Dreyer, and W. N. Hubbard, *J. Am. Chem. Soc.*, **83**, 606 (1961).

(5) E. S. Huyser and R. M. Kellogg, *J. Org. Chem.*, **30**, 3003 (1965).

(6) E. J. Corey and R. A. Sneen, *J. Am. Chem. Soc.*, **77**, 2505 (1955).

I are subjected to angular strain. Quite interestingly, Corey and Sneen showed the cyclohexylidene ring system (X) with only one sp^2-hybridized carbon to be

X

free of angular strain. Addition of RS· to I yielding A· is a reaction in which a relief of angular strain is encountered because the adduct radical has a single sp^2-hybridized carbon, and there would be essentially no angular strain in either ring of A·. On the other hand, elimination of RS· from A· to yield I would be a reaction in which angular strain would be introduced into both rings of the alkene. Consequently, it might be expected that elimination of RS· from A· may be a slower reaction than reaction of A· with mercaptan yielding the addition product and, as pointed out earlier, the mercaptan concentration would have little effect on the product ratio in such a case.

The proposed irreversible addition of RS· to I can be supported experimentally by competition reactions of I and 1-decene (an alkene which does undergo reversible addition of RS·). The data in Table II show that as the mercaptan-to-alkene ratio is decreased, the reactivity of I relative to that of 1-decene toward addition by methyl mercaptan (k_I/k_X) increases as would be predicted if the addition of the thiyl radical to I is not appreciably reversible but the addition to 1-decene is reversible.

$$CH_3S\cdot + I \longrightarrow A\cdot\ (+ B\cdot) \xrightarrow{CH_3SH} II\ (+ III) + CH_3S\cdot$$

$$CH_3S\cdot + CH_2{=\!=}CHC_8H_{17}\text{-}n \rightleftharpoons CH_3SCH_2\dot{C}HC_8H_{17}\text{-}n \xrightarrow{CH_3SH} CH_3SC_{10}H_{21}\text{-}n + CH_3S\cdot$$

TABLE II

COMPETITION REACTIONS OF I AND 1-DECENE WITH METHYL MERCAPTAN (40°)

Mercaptan/total alkene	Initial amounts × 10^4 moles I	Initial amounts × 10^4 moles 1-Decene	Final amounts × 10^4 mole I	Final amounts × 10^4 mole 1-Decene	k_I/k_X
6.70	6.82	5.79	6.05	2.29	0.13
1.07	8.85	5.47	4.07	1.66	0.65
1.22	10.68	6.33	8.24	4.38	0.71
0.427	10.25	4.96	7.66	4.07	1.51

Experimental Section[7]

trans-Δ^2-Octalin was prepared by the method described by Johnson and co-workers,[4] bp 50° (4 mm), n^{25}D 1.4794. All other reagents were commercial materials.

Methyl Mercaptan and *trans*-Δ^2-Octalin.—A mixture of methanethiol (1.52 g, 0.032 mole) and *trans*-Δ^2-octalin (2.6 g, 0.019 mole) was sealed in a Pyrex tube and illuminated with a 275-w sun lamp for 24 hr in a water bath set at 40°. After removal of the unreacted mercaptan by allowing it to distill from the reaction mixture at room temperature, the resulting mixture of addition products was subjected to gas chromatographic analysis which showed the presence of one large component and a smaller one. A portion of this mixture was separated by preparative gas chromatography (10 ft × $^3/_8$ in. column packed with 30% diethylene glycol succinate on Chromosorb W). The sulfones of the separated sulfides were prepared by treatment of an acetic acid solution of each with 30% hydrogen peroxide. The sulfone of the major component melted at 119–120°.

Anal. Calcd for $C_{11}H_{10}O_2S$: C, 61.07; H, 9.34. Found: C, 61.02; H, 9.09.

Reaction of this sulfone with sodium ethoxide in refluxing ethanol for 3 days yielded an isomeric sulfone which melted at 88°. This sulfone showed no depression in melting point when mixed with the sulfone obtained from the minor component which also melted at 88°.

Anal. Calcd for $C_{11}H_{20}O_2S$: C, 61.07; H, 9.34. Found: C, 60.77; H, 9.23.

After heating the lower melting sulfone in refluxing ethanol with an excess of sodium ethoxide, the sulfone was recovered unchanged.

Effect of Concentration on Product Distribution.—Between 0.05 and 0.13 g of *trans*-Δ^2-octalin was accurately weighed into a weighed Pyrex tube. Methyl mercaptan was condensed in the tube after the tube was flushed with N_2 and cooled in a Dry Ice–Cellosolve bath. The tube was sealed, and the amount of mercaptan added was determined by weighing the two parts resulting from the sealing operation. The sealed tube was placed in a constant-temperature water bath, maintained at 40°, and illuminated with a 275-w sun lamp for 11 hr. After cooling in a Dry Ice–Cellosolve bath, the tube was opened and any unreacted methanethiol was allowed to evaporate slowly. The resulting reaction mixture was subjected to gas chromatographic analysis on a 10 ft × 0.25 in. copper column packed with 12% diethylene glycol succinate on Chromosorb P. The amounts of each addition product were determined from their peak areas which were measured by a compensating polar planimeter. The data obtained from these studies are shown in Table I.

Ethanethiol and *trans*-Δ^2-Octalin.—A mixture of ethyl mercaptan (2.88 g, 4.65 mmoles) and *trans*-Δ^2-octalin (1.39 g, 1.02 mmoles) was sealed in a Pyrex tube and illuminated at ambient room temperature for about 10 min. Distillation of the resulting mixture yielded 1.2 g (60% of theory) of a mixture of the equatorial and axial 2-ethanethio-*trans*-decalins, bp 113° (2.8 mm), n^{20}D 1.5095.

Anal. Calcd for $C_{12}H_{22}S$: C, 72.66; H, 11.17; S, 16.17. Found: C, 72.64; H, 11.14; S, 16.19.

Gas chromatographic analysis of the mixture indicated that one of the sulfides predominated over the other by a factor of about 12:1. Reaction of 1 g of the sulfide mixture in 10 ml of acetic acid with 30% hydrogen peroxide yielded, after one recrystallization of methanol, 0.9 g (77% of theory) of a mixture of sulfones that melted over a range of 61–62.5°.[8]

Anal. Calcd for $C_{12}H_{22}SO_2$: C, 62.57; H, 9.62; S, 13.92. Found: C, 62.43; H, 9.63; S, 13.70.

Reaction of a portion of this sulfone with sodium ethoxide in ethanol in a sealed tube at 100° overnight yielded the sulfone of the equatorial isomer (melting point from 50% ethanol–water was 70–70.8°).

Anal. Calcd for $C_{12}H_{22}SO_2$: C, 62.57; H, 9.62; S, 13.92. Found: C, 62.20; H, 9.65; S, 13.35.

Other reactions of ethanethiol and *trans*-Δ^2-octalin performed by adding the mercaptan dropwise to the olefin and by adding the olefin dropwise to the mercaptan yielded mixtures which on gas chromatographic analysis showed the ratio of axial isomer to equatorial isomer to be essentially the same.

Competition Reactions of *trans*-Δ^2-Octalin and 1-Decene with Methyl Mercaptan.—Mixtures consisting of *trans*-Δ^2-octalin, 1-decene, and chlorobenzene, which served as an internal standard for the gas chromatographic analysis, were accurately weighed into a Pyrex tube. A portion of each mixture was subjected to gas chromatographic analysis on a 4 ft × 0.25 in. column packed with silicon rubber on Chromosorb. A quantity of methyl mercaptan was condensed in each tube, the tubes were sealed, and from the weight of the two portions of the tubes the amounts of mercaptan added were determined. The reaction mixtures were illuminated at 40° for 30 min. After cooling, the tubes were opened and the unreacted mercaptan was allowed to evaporate. A portion of each of the resulting mixtures was chromatographed on the same column under the same conditions used for the analysis of the reaction mixtures before illumination. The quantities of the two alkenes remaining were determined by com-

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(7) Melting points are uncorrected. Elemental analyses were performed by Hufman Laboratories, Boulder, Colo., and analytical laboratories of the Department of Organic Chemistry, University of Groningen, Groningen, The Netherlands.

(8) The sulfone of the major component of another reaction mixture separated by preparative gas chromatography also melted at 61–62.5°.

parison of their peak areas with those found before illumination. Necessary corrections for differences in the quantities chromatographed were made from the peak areas of the chlorobenzene. The data obtained from these studies are shown in Table II.

Registry No.—I, 2001-50-5; VI and VII, 7430-63-9; IV and V, 7430-64-0; VIII and IX, 7430-65-1.

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Phenoxy Radical Intermediates. II.[1a] The Oxidative Detoxification of Phenols in Incense Cedar Heartwood

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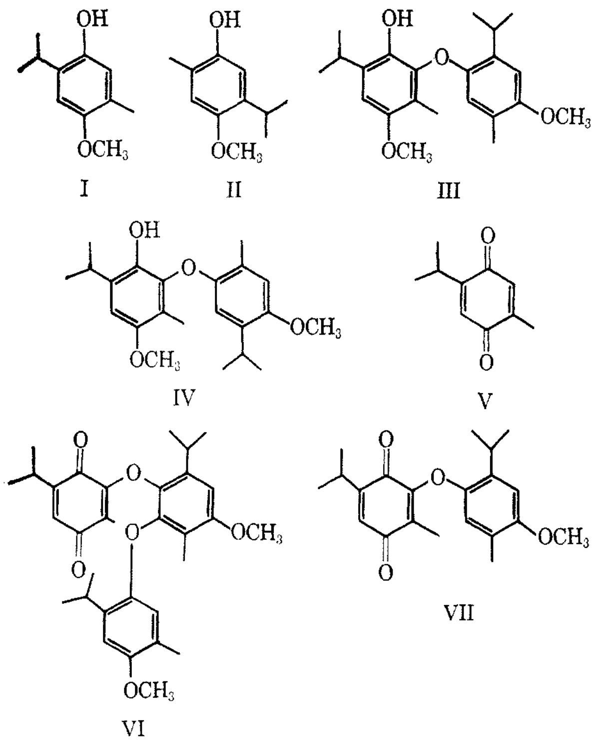
The fungicidal phenols, *p*-methoxythymol (I) and *p*-methoxycarvacrol (II), are converted to stable radical species upon oxidation. Their naturally occuring detoxification products, libocedrol (III) and heyderiol (IV), form unusually stable radical species upon further oxidation. Hyperfine coupling constants are assigned to all phenoxyls. Their role in the detoxification mechanism is discussed, as well as their individual properties.

The decay-resistant properties of incense cedar (*Libocedrus decurrens*, Torrey) have been attributed to the presence of the fungicidal phenols, *p*-methoxythymol (I) and *p*-methoxycarvacrol (II).[2] Decrease of decay resistance with aging of the wood is concommitant with the decrease in concentration of I and II, and the increase in the concentration of the diaryl ethers, libocedrol (III) and heyderiol (IV), as well as the increase of thymoquinone (V), 3-libocedrothymoquinone (VI), and libodedroquinone (VII) (Chart I).

Chart I



It has been proposed[2,3a] that phenols I and II were oxidized to phenoxy radical intermediates (Ia and IIa), which then undergo a variety of coupling reactions to yield dimeric and trimeric products.[3b] We now wish to report the isolation and characterization of these intermediates, by means of electron spin resonance (esr) spectroscopy.

Results

Esr Spectra in Benzene.—When dilute (10^{-3} *M*) solutions of I and II in benzene are oxidized with PbO_2, low concentrations of radical species Ia and IIa were obtained. An analysis of the esr spectra (Figures 1–3), aided by a computer program designed to plot synthetic spectra,[4] established the following hyperfine coupling constants for the species (Table I). The radicals appeared to be stable for many hours in deoxygenated solutions under nitrogen.

Table I
Coupling Constants[a] in Benzene

Radical	$H_{\text{isopropyl}}$	H_{CH_3}	H_{ring}	H_{OCH_3}
Ia	3.20(1)	1.60(3)	0.80(1)[b]	1.60(3)
IIa	1.53(1)	7.65(3)	1.53(2)[c]	1.53(3)
IIIa	2.80(1)	1.40(3)	...	1.40(3)
IVa	2.80(1)	1.40(3)	...	1.40(3)

[a] In gauss. Numbers in parenthesis indicate number of protons. [b] *ortho* ring proton. [c] *ortho* and *meta* ring protons.

The oxidation of libocedrol (III) and heyderiol (IV) under identical conditions produced strong esr signals, indicating a high concentration of radical species IIIa and IVa. As might be anticipated from their structures, the spectra of IIIa and IVa were identical. The coupling constants (Table I) reflect their similarity to Ia, differing notably in the absence of any interac-

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(1) (a) Part I of this series: C. Steelink, *J. Am. Chem. Soc.*, **87**, 2056 (1965). (b) To whom requests for reprints should be sent.

(2) (a) A. B. Anderson, T. C. Scheffer, and C. G. Duncan, *Holzforschung*, **17**, 1 (1963); (b) *Chem. Ind.* (London), 1289 (1962).

(3) (a) E. Zavarin, *J. Org. Chem.*, **23**, 1198 (1958). (b) Theoretically, four products are possible for the dimerization of Ia and IIa. However, only III and IV were isolated by Zavarin.[5a]

(4) We are indebted to Professor John Harriman of the Department of Chemistry, University of Wisconsin, and Professor Leslie Forster of the Department of Chemistry, University of Arizona, for writing this program.