(**12**). Compound **12** was obtained as a glass which resisted crystallization, although it appeared homogeneous on the basis of LC analysis: $[\alpha]_D^{EtOH}$ +36.6° (*c* 0.45); $^1$H NMR $\delta$ 0.92 (3, s), 1.19 (3, t, $J$ = 7 Hz), 1.22 (3, s), 1.3-2.6 (18, m), 1.95 (3, s), 3.90 (1, br, exchanges with $D_2O$), 4.10 (1, d of d, $J$ = 9, 6 Hz), 4.40 (1, br d, addition of $D_2O$ simplifies to d, $J$ = 12 Hz), 5.12 (1, d of t, $J$ = 12, 3, 3 Hz), 5.56 (1, br d, $J$ = 2 Hz), 6.30 (1, d, $J$ = 10 Hz), 7.43 (1, d, $J$ = 2 Hz), 7.80 (1, d of d, $J$ = 10, 2 Hz); the $^{13}$C NMR spectrum of **12** corresponds closely to that of **5**, except that the acetate ester absorptions at $\delta$ 169.2 and 20.7 are replaced by propionate ester absorptions[22] at 172.9 (s, C=O), 29.8 (t, $CH_2$), and 8.7 (q, $CH_3$); EIMS (70 eV) *m/e* (rel intensity) 546 ($M^+$, 1), 528 ($M^+ - H_2O$, 2), 394 (3), 376 (1), 221 (10), 204 (16), 191 (14), 175 (10), 136 (5), 135 (10), 123 (14), 57 (71), 43 (100).

**12-Oxo-2β-*O*-acetyl-3β,11α-di-*O*-propionyl-5β-hydroxybufalin** (**16**). Propionyl chloride (100 μL) was added dropwise to a solution of **6** (100 mg, 0.2 mmol) in pyridine (1 mL) and the resulting solution stirred at room temperature. Portions of the reaction mixture were removed for periodic analysis by LC. The initial reaction product corresponded in $R_t$ to compound **12** and as the reaction progressed a second product of slightly longer retention time was observed. Evaporation of the volatile material in vacuo and purification of the residue by column chromatography gave **16** as a viscous oil (92 mg, 76%): the $^1$H NMR spectrum of **16** was very similar to that of the triacetate **8**, with the resonances of two propionate esters ($\delta$ 1.16 (3, t, $J$ = 7 Hz), 1.17 (3, t, $J$ = 7 Hz), 2.35 (4, q, $J$ = 7 Hz)) replacing the acetate resonances of **8**; EIMS (70 eV) *m/e* (rel intensity) 602 ($M^+$, 0.2), 584 ($M^+ - H_2O$, 0.2), 394 (5), 205 (17), 204 (7), 191 (15), 175 (6), 135 (6), 123 (4), 57 (100), 43 (35).

Treatment of compound **12** with propionyl chloride under identical conditions also gave **16**, while treatment of **7** with propionyl chloride gave a different compound.

**Acknowledgments.** We are grateful to Professors W. D. McElroy and M. DeLuca for their generous gifts of *P. pyralis*, to Professors Ch. Tamm and K. Meyer (University of Basel) for providing authentic samples of bufadienolides, and to Mr. Steven Burke (University of Pittsburgh) for his assistance in obtaining the 250-MHz spectrum of **5**. Partial support of this work by the National Institutes of Health (Fellowship Award CA 05646 (D.F.W.) and Grant No. AI 12020) is acknowledged with pleasure.

## References and Notes

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# Identity of the Chain-Carrying Species in Halogenations with Bromo- and Chloroarylalkoxyiodinanes: Selectivities of Iodinanyl Radicals

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**Abstract:** The free-radical halogenation of substituted toluenes by haloiodinanes **2a–b** and **3a–b** in benzene solvent is highly selective for benzylic hydrogens. The process involves cyclic iodinanyl radicals, except in the case of **3b**, which appears to react via a bromine atom chain. The essentially identical values of $\rho^+$ for **2a** (−1.46) and **2b** (−1.48) are consistent with there being a common chain-carrying species for both bromination and chlorination. Identical $\rho^+$ values were not observed for **3a** (−1.31) and **3b** (−1.55 vs. Br, −1.58). Such iodinanyl radicals, unlike those derived from phenyliodine dichloride, are constrained to a C-I-O angle far smaller than 180°, allowing an opportunity to study the effects of bending on radical selectivities. The intermediacy of iodinanyl radicals in free-radicals chlorinations is further supported by evidence from photoinitiated reactions of **2a** and **3a** with 2,3-dimethylbutane. Comparisons of selectivities with those determined in other studies show that chlorine atoms are not involved. The allylic chlorinations of *cis*- and *trans*-2-butenes by **2a** and **3a** were studied and found to be selective, high-yield reactions which give little or no addition to the carbon-carbon double bond.

## Introduction

Organic compounds of tricoordinate iodine(III) may be generally designated as hypervalent[1] iodine species and more specifically as iodinanes.[2] The formation of iodine-centered radical intermediates from such iodinanes, since it involves breaking weak bonds to iodine, is expected to be an energetically favorable process.

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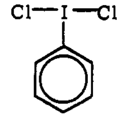
**Table I.** Slopes ($\rho^+$) for Halogenations of Substituted Toluenes (50 °C, Benzene Solvent)[a]

| reagent | slope, $\rho^+$ |
|---|---|
| Chlorination | |
| $Cl_2$[b] | −1.01 |
| $t$-$C_4H_9OCl$ (40 °C)[c] | −0.75 ($\rho$) |
| **1**[b] | −1.51 |
| **2a**[b] | −1.46 |
| **3a**[b] | −1.31 |
| Bromination | |
| *N*-bromosuccinimide[b] | −1.58 |
| **2b**[b] | −1.48 |
| **3b**[b] | −1.55 |

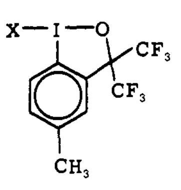
[a] Slopes of log $k_{rel}$ vs. $\sigma^+$ plot. [b] This work. [c] R. D. Gilliom and B. F. Ward, Jr., ref 13, found a correlation with $\sigma$ rather than $\sigma^+$.

An iodinanyl radical intermediate was first suggested by Russell[3] to explain the chlorination reactions of molecular chlorine in the presence of iodobenzene solvent. The same iodinanyl radical was postulated as an intermediate in the photoinitiated chlorination reactions of phenyldichloroiodinane (**1**).[4,5] The intermediacy of iodinanyl radicals has also been proposed in the iodination reactions of *tert*-butyl hypoiodite,[6] in several intramolecular hypoiodite reactions,[7] in the decompositions of iodinated peroxides[8a-c] and peresters,[8d] and in the chlorination reactions of the iodinane derived from the oxidation of iodobenzene by *tert*-butyl hypochlorite.[9]

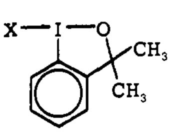


**1**

Breslow[10] has concluded that iodinanyl radicals are involved in the chlorination of steroids which are mediated by covalently bound aryl iodide "templates". These provide a synthetically useful method for the selective functionalization of unactivated sites in the attached steroid. The chloroiodinanyl radicals postulated to be important here, like those which are intermediates in radical chlorinations with dichloroiodinane **1**, have few constraints imposed on the geometry about iodine by other structural features of this molecule. The cyclic structures of the iodinanyl radicals derived from **2a,b** and **3a,b**, on the other hand, require C-I-O angles much less than 180°. The "bent" iodinanyl radicals could perhaps show changes in selectivity which could be correlated with angle strain. The implications of Breslow's template approach to synthesis provides added interest to the study of iodinanyl radical selectivities.



**2a**, X = Cl
**2b**, X = Br
**2c**, X = F



**3a**, X = Cl
**3b**, X = Br

Our approach to this question has led us to study the highly selective free-radical halogenations effected by a series of bromo- and chloroarylalkoxyiodinanes, **2a,b** and **3a,b**.

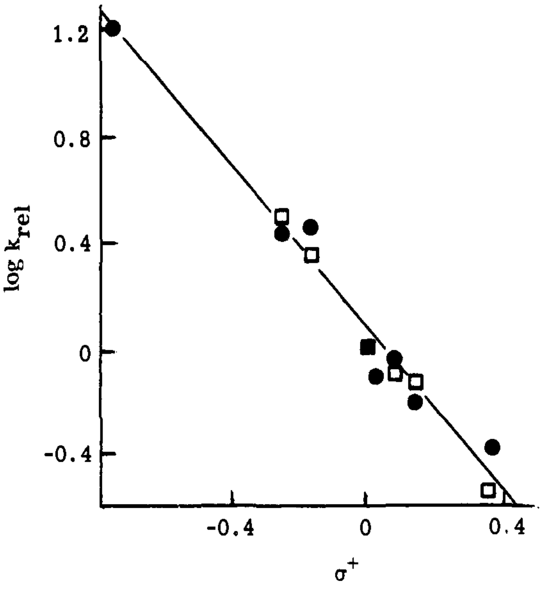


**Figure 1.** Halogenation of substituted toluenes with iodinanes **2a** and **2b**: ●, **2a**, $r$ = 0.9867; □, **2b**, $r$ = 0.9965; **2a** and **2b**, $\rho^+$ = −1.47, $r$ = 0.9998.

## Results

**Halogenation of Substituted Toluenes.** A comparison of the selectivities of several chlorinating agents is shown in Table I. An excellent fit of the points to the Hammett correlation is obtained when Brown's[11,12] $\sigma^+$ values are used. The $\rho^+$ values for chloroiodinanes **1** (−1.51), **2a** (−1.46), and **3a** (−1.31) differ substantially from those of chlorine atom (−1.01) and *tert*-butyl hypochlorite (−0.75). The following substituted toluenes gave the relative rate constants shown in parentheses for benzylic chlorinations: **2a**, $p$-$OCH_3$ (13.7), $p$-$CH_3$ (2.88), $p$-$(CH_3)_3C$ (2.50), H (1.00), $m$-$OCH_3$ (0.85), $p$-Cl (0.68), $p$-Br (0.60), and $m$-F (0.31); **3a**, $p$-$CH_3$ (2.6), $p$-$(CH_3)_3C$ (2.2), H (1.00), $m$-F (0.35), and $m$-Br (0.29).

The analogous $\rho^+$ values for brominations by **2b** (−1.48), **3b** (−1.55), and *N*-bromosuccinimide (NBS) (−1.58) are shown in Table I (phenyldibromoiodinane is not known). Brominations of methoxytoluenes by **2b** or **3b** show significant amounts of nuclear bromination. These data are therefore omitted from the statistical calculations. The following relative rates for benzylic bromination (in parentheses) were observed for substituted toluenes: **2b**, $p$-$CH_3$ (2.91), $p$-$(CH_3)_3C$ (2.35), H (1.00), $p$-Cl (0.68), $p$-Br (0.59), and $m$-F (0.30); **3b**, $p$-$OCH_3$ (15.4), H (1.00), $m$-F (0.27), and $m$-Br (0.23).

When bromination data for **2b** and chlorination data for **2a** are considered together, in correlations with $\sigma^+$, the correlation coefficient, $r$ (0.9998), is greater than that for either of the individual sets of data (**2a**, $r$ = 0.9862; **2b**, $r$ = 0.9965). For the correlation of relative rate constants with $\sigma^+$ values, see Figure 1.

Application of the Student $t$ test[12] to these data show that the benzylic chlorination with **2a** and bromination with **2b** proceed with the same selectivity within 98% confidence levels. The selectivities shown in halogenations by **3a** and **3b** are different within 98% confidence levels.

**Chlorination of 2,3-Dimethylbutane.** A comparison of the selectivities shown by **2a** and **3a** in the photochlorination of 2,3-dimethylbutane with those shown by other chlorinating agents, expressed in terms of the ratio of tertiary to primary abstraction (per hydrogen atom), is shown in Table II.

**Allylic Halogenations.** The irradiation of *cis*- or *trans*-2-butene in the presence of chloroiodinane **2a** or **3a** at 40 °C results in, respectively, either the *cis*- or *trans*-1-chloro-2-butene and 3-chloro-1-butene. The amount of other products,

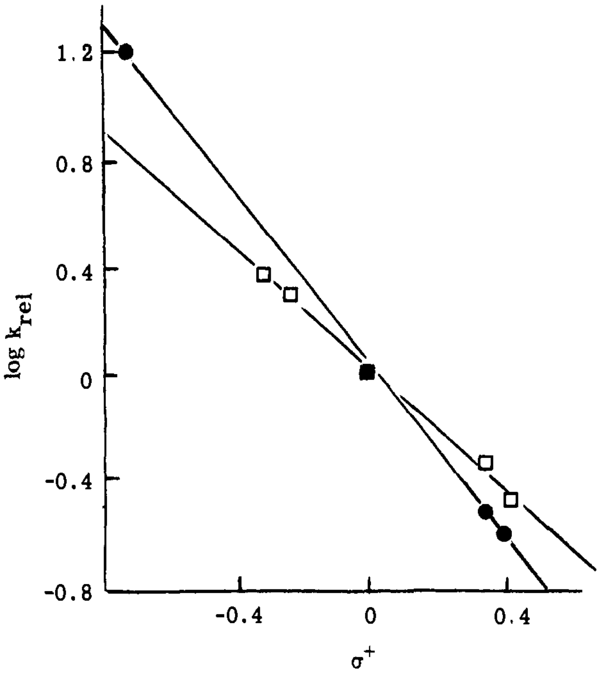


**Figure 2.** Halogenations of substituted toluenes with iodinanes **3a** and **3b**: □, **3a**, $\rho^+ = -1.31$, $r = 0.9989$; ●, **3b**, $\rho^+ = -1.55$, $r = 0.9998$.

**Table II.** Comparison of the Selectivities of Chlorinating Agents for Primary and Tertiary Hydrogen Atoms of 2,3-Dimethylbutane[a]

| reagent | rel rates, tertiary/primary[b] | reagent | rel rates, tertiary/primary[b] |
|---|---|---|---|
| $Cl_2$ (27 °C)[c] | 5.1 | **3a** (50 °C)[f] | 265 |
| $t$-$C_4H_9OCl$ (40 °C)[d] | 44 | **2a** (50 °C)[f] | 352 |
| $C_6H_5ICl(O$-$t$-$Bu)$ (40 °C)[e] | 144 | **1** (40 °C)[g] | 368 |

[a] Photoinitiated, $CCl_4$ solvent, 10:1 substrate:reagent ratio. [b] Per hydrogen basis. [c] P. C. Anson, P. S. Fredericks, and J. M. Tedder, *J. Chem. Soc.*, 918 (1959). [d] C. Walling and B. B. Jacknow, *J. Am. Chem. Soc.*, **82**, 6108 (1960). [e] Reference 9. [f] This work. [g] Reference 5a.

thought to be addition products, is in every case <10%. No measurable amounts of cis-trans isomerization were observed by $^1H$ NMR spectroscopy (<5% limit of detectability). The results of the allylic halogenations are shown in Table III.

## Discussion

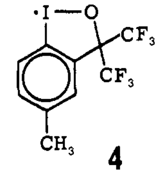
**Halogenations of Substituted Toluenes.** The competitive halogenations of substituted toluenes provide a probe for the investigation of the selectivity of the radical chain-carrying species. The photohalogenations of a series of substituted toluenes by chloroiodinane **2a** and by bromoiodinane **2b** were carried out at 50 °C, in benzene. Relative rate constants for the halogenations by iodinanes **2a** and **2b** gave excellent correlations with $\sigma^+$ values[11,12] (Figure 1, $\sigma^+ = -1.47$), with a high probability (vide supra) that the two halogenating agents show the same selectivity in benzylic halogenations. This suggests the action of the same chain-carrying hydrogen-abstracting radical in reactions of **2a** and **2b**, with a selectivity different from those for chlorine atoms (−1.01), bromine atoms (−1.58), and *tert*-butoxy radicals ($\rho = -0.75$, 40 °C).[13]

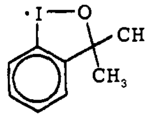
Recent work of Giese[14] has pointed up the fact that selectivities in certain radical displacement reactions, as reflected in $\rho^+$ values, can be strongly temperature dependent. The identity of $\rho^+$ values for **2a** and **2b** is established for only one temperature (50 °C). This is, however, a temperature at which the other plausible chain-carrying radicals (Cl·, Br·, and RO·) have very different selectivities.

**Table III.** Selectivities (Primary/Secondary Product Ratios, Percent) in Allylic Chlorinations of *cis*- and *trans*-2-Butene with Various Chlorinating Agents[a]

| olefin | *tert*-$C_4H_9OCl$[b] | **2a**[c] | **3a**[c] |
|---|---|---|---|
| *cis*-2-butene[d] | 63:37 | 79:21 | 84:16 |
| *trans*-2-butene[d] | 73:27 | 80:20 | 88:12 |

[a] 40 °C, butene as solvent. [b] Reference 22. [c] This work. [d] Ratios of 1-chloro-2-butene (cis or trans) to 3-chloro-1-butene; addition products were <10% of total. No isomerization observed (<5% by $^1H$ NMR spectroscopy).

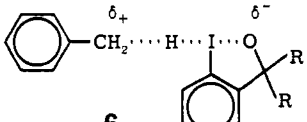

**4**


**5**

The fact that both bromination and chlorination proceed via the same radical species is very unusual. Few reagents are known in which two different halogenation reactions proceed through a common radical species. Brominations performed with *tert*-butyl hypobromite[15] are thought to provide a mechanistic parallel to chlorinations by *tert*-butyl hypochlorite, with a hydrogen-abstraction step utilizing *tert*-butoxy radical in both cases. Further work is needed to confirm this conclusion, however, and other cases of possible common bromination-chlorination hydrogen-abstracting intermediates also remain obscure.[16]

The *gem*-dimethyliodinanes **3a** and **3b** do not show equal selectivities in their reactions with toluenes (vide supra). Chlorinations of substituted toluenes by **3a** show a $\rho^+$ value (−1.31, Figure 2), substantially different from that of chlorine atom (−1.01) and of *tert*-butoxy radicals ($\rho = -0.75$, 40 °C).[13] A *gem*-dimethyliodinanyl radical, **5**, must act as the abstracting species for the chlorination reaction. This is not the case for brominations by **3b**, which show a $\rho^+$ value (−1.55), identical, within experimental error, with that of bromine atom (−1.58). The hydrogen-abstracting species in halogenations by **3a** and **3b** are clearly different. The small difference in $\rho^+$ values for **3b** and for *N*-bromosuccinimide (NBS) suggests that brominations by **3b** may also proceed by a bromine atom chain. The reaction of **3b** with hydrogen bromide to give bromine was found to be fast, making it seem likely that the mechanism is in this case closely analogous to that which operates in many brominations with NBS.[17]

The polar effects, which result from the polarizations of the transition state **6** (a generalized structure), are much greater for the trifluoromethyl species **2a–b** than for the *gem*-dimethyl analogue **3a**. These differences, due to the higher apical ligand electronegativity of **2a–b** ($CF_3$ groups) relative to that of **3a** ($CH_3$ groups), can account for the lower selectivity seen for **3a** relative to its trifluoromethyl analogues, **2a–b**.


**6**

**2,3-Dimethylbutane Chlorinations.** The photochlorination of 2,3-dimethylbutane by chloroiodinanes **2a** and **3a** confirms our conclusion that cyclic alkoxyiodinanyl radicals are very selective hydrogen-abstracting species. Analogous work by Tanner and Van Bostelen[5a] with phenyldichloroiodinane **1** indicates that acyclic iodinanyl radicals (i.e., $\mathrm{Ph\dot{I}Cl}$) are also highly selective hydrogen-abstracting radicals in this system.

A comparison of the selectivities for tertiary C–H relative to primary C–H abstraction for chlorination of 2,3-dimethylbutane by chlorine (5.1), *tert*-butyl hypochlorite (44), **1** (368), **2a** (352), and **3a** (265) is shown in Table II. The data clearly indicate that all of these chlorinations show a greater selectivity than chlorinations with chlorine atom chains. The conclusion that none of the three iodinanes chlorinates primarily via a chlorine atom chain strengthens our postulate of an iodinanyl radical intermediate. Because the observed selectivity for hydrogen abstraction is a qualitative measure of the abstracting radical stability, as well as of the C–H bond strength, our results suggest that cyclic iodinanyl radicals may be slightly less stable, hence, less selective, than the acyclic analogue, $\mathrm{Ph\dot{I}Cl}$. The differences in selectivities are small enough, however, to suggest that no pronounced effect of bending of the C–I–O angle in the cyclic iodinanyl radicals is manifested in these reactions. This is consistent either with the postulate that the chloroiodinanyl radical from **1** ($\mathrm{Ph\dot{I}Cl}$) is nonlinear or that the selectivity in hydrogen atom abstraction by iodinanyl radicals is not sensitive to bending of the C–I–X bond.

The lower selectivity of *gem*-dimethyliodinane **3a**, relative to that of trifluoromethyl analogue **2a**, is consistent with the postulate that **3a** is slightly less stable, and therefore less selective than **2a.**

**Allylic Halogenations.** Reagents which perform selective, high-yield allylic halogenations are not numerous. Only *tert*-butyl hypochlorite, which usually chlorinates by a *tert*-butoxy radical chain,[18] and NBS, which usually brominates by a bromine atom chain,[17,19] have proven useful in this respect. The *tert*-butoxy radical reacts with olefins preferentially by allylic hydrogen abstraction, rather than by addition to the double bond.[20] Poutsma[21] found that 1- and 2-butenes give >80% of allylic chlorination in these reactions with *tert*-butyl hypochlorite, in contrast to the addition reaction given by chlorine.

Barton and Miller[22] found that **1** adds to cholesteryl benzoate to give *cis*- and *trans*-5,6-dichloro products. Iodinane **1** also adds the elements of chlorine to the double bond of norbornene.[5b,23] In no cases have allylic chlorinations been observed.

Cyclic chloroiodinanes **2a** and **3a** and cyclic bromoiodinane **2b** give allylic halogenation of cyclohexene.[24] The reaction, which was followed by $^1$H NMR spectroscopy, gives a 95% yield of the 3-halocyclohexenes. No addition to the double bond is observed.

After storage in the dark at times longer than those required for complete reaction by irradiation, yellow solutions of **2a** or **3a** with *cis*- or *trans*-2-butene are not decolorized and $^1$H NMR spectroscopy shows no change. This is consistent with photoinitiation of a radical-chain process for these allylic chlorinations (Table III).

A small amount (<10%) of a possible addition product accompanies the allylic halogenation reaction of 2-butenes with these iodinanes. The thermodynamically favored products, the 1-halo-2-butenes, retain their cis–trans stereochemistry (an upper limit of 5% isomerization, determined by $^1$H NMR spectroscopy). The intermediate allylic radicals retain stereochemical integrity under these reaction conditions. The product allylic isomer ratio from a specific allylic radical favors the more substituted olefin. Walling[20] obtained similar results under certain conditions for the reaction of *tert*-butyl hypochlorite with 2-butenes.

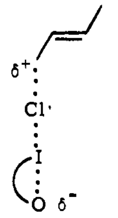
The ratios of product 1-chloro-2-butene to 3-chloro-1-butene are higher for the haloiodinanes (4 for *trans*- or *cis*-2-butene with **2a**, 7.3 for *trans*-2-butene with **3a**, and 5.3 for *cis*-2-butene with **3a**) than for *tert*-butyl hypochlorite (2.7 for *trans*-2-butene and 1.7 for *cis*-2-butene).[22]

Two factors influence the ratio of the 1-chloro-2-butene to 3-chloro-1-butene: (1) the steric bulk in the vicinity of the chlorine which is abstracted by an allylic radical (the product-determining step); (2) the stabilities of the product olefins. Chlorine abstraction from the haloiodinanes is more subject to steric hindrance than that from the hypochlorite because of the larger steric bulk in the vicinity of the chlorine in the iodinanes. This leads to a higher steric selectivity for the iodinanes and hence, a larger primary/secondary ratio. This effect on the ratio is superimposed on the general effect of product stabilities.

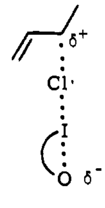
To the extent that the transition state for chlorine atom transfer resembles products the thermodynamically favored primary chloride is also kinetically favored. Since the allylic rearrangement of the secondary to the primary allylic chloride would give a mixture of *cis*- and *trans*-1-chloro-2-butene, the failure to see cis–trans isomerization in product chlorides from either *cis*- or *trans*-2-butene provides evidence that the product chlorides are not interconverted under the conditions of these reactions and the observed preference for primary chloride is kinetic in origin.

In view of the proposed importance of steric effects in determining the ratio of primary to secondary allylic halides it is perhaps surprising to note that for **3a** the reaction with *cis*-2-butene shows a lesser selectivity than that with *trans*-2-butene. This effect has also been observed for reaction of *tert*-butyl hypochlorite with the 2-butenes.[20]

The *gem*-dimethyliodinanes are slightly (less than a factor of 2) more selective than the trifluoromethyl analogues, based on the primary/secondary ratios. This may be attributed, in part, to the role that polar effects play in product determination, superimposed on the larger overall effects of steric bulk and product stabilities. The product-determining step can be pictured in two ways (**7a** and **7b**). (The drawings of **7a** and **7b** represent the ring joining O to I schematically as a curved line joining these atoms.)



**7a**



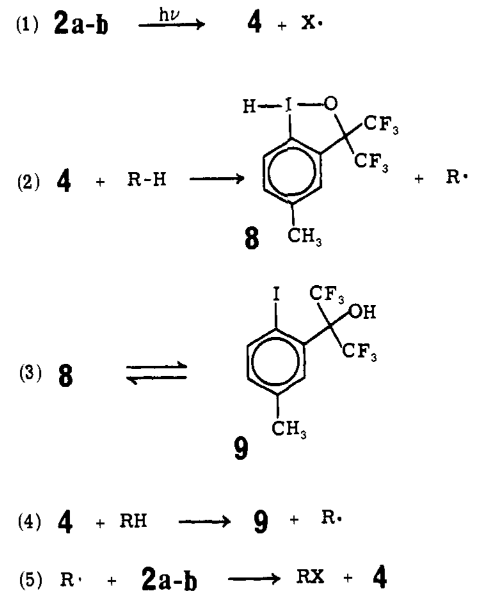
**7b**

To the extent that the pictured polarization plays some role in product determination, the more polar trifluoromethyl case, which places more positive charge on the secondary carbon, is expected to favor structure **7b.** This structure, which is lower in energy for the $CF_3$ species, explains the observed lesser amount of primary product for the $CF_3$-substituted case.

**Mechanisms of Halogenations.** The photoinitiated halogenations of substituted toluenes and of olefins by haloiodinanes **2a–b** and **3a** may proceed as illustrated in Scheme I. It depicts halogenations by trifluoromethyl iodinanes **2a–b** but is equally applicable to the *gem*-dimethylchloroiodinane **3a.** It does not, however, apply to brominations by **3b**, which are expected to follow a mechanism reminiscent of the bromine atom chain process established[17] for benzylic halogenations by NBS.

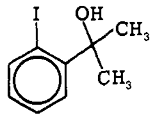
The photoinitiation as depicted here involves I–X bond cleavage in the iodinane, although it is possible that trace amounts of chlorine or bromine are involved in the initiation step. The product-determining steps for the competitive ben-

Scheme I

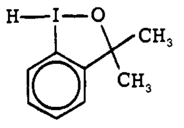


zylic halogenation and for the allylic halogenations studied here are, respectively, steps 2 (or 4) and 5. We cannot at this time distinguish between the benzylic hydrogen abstraction at iodine (steps 2 and 3) and the abstraction at oxygen (step 4). The former leads to a hydridoiodinane (**8**) which might subsequently collapse to the iodo alcohol **9**, while the latter gives **9** directly.

It is pertinent that we have found $^1$H NMR spectroscopic evidence which suggests that, at least in some cases, iodo alcohols such as the *gem*-dimethyl analogue,[24] **10**, may exist as the cyclic hydridoiodinane **11**. A proton ortho to a hypervalently bonded heteroatom, where the heteroatom is incorporated into an apical-equatorial linked five-membered ring (such as the iodine of these iodinanes), shows a distinctive low-field chemical shift in a large variety of hypervalent compounds.[24-26] This low-field chemical shift, in compounds where the aromatic ring, the heterocyclic ring, and the apical hypervalent bond are essentially coplanar, has proven to be a reliable indicator for such structural features in sulfuranes,[25] phosphoranes,[26a] and pentacoordinated silicon derivatives,[26b] as well as the iodinanes of this study.[24]



**10**



**11**

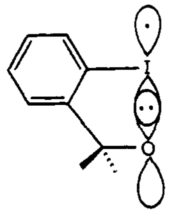
The chemical shift of the ortho proton in haloiodinanes **2a-b** and related dialkoxyiodinanes[24] is 0.8-1.0 ppm downfield of that for the parent iodo alcohol **9**. The *gem*-dimethyl analogue, **10**, has its ortho hydrogen signal ($\delta$ 8.2) shifted downfield relative to that of *o*-iodobenzyl alcohol (7.8),[27a] and of *o*-iodobenzoic acid (8.0).[27b] Although the magnitude of the shift is not large, it is comparable with that seen for the *gem*-dimethyliodinanes (**3a**, $\delta$ 8.0; **3b**, $\delta$ 8.3)[24] relative to *o*-iodobenzyl alcohol and *o*-iodobenzoic acid, suggesting that **10** may exist in the cyclic, hydridoiodinane form, **11**.

While the evidence is not conclusive for the presence of **11**, it suggests that such a species may exist and play a role in the hydrogen abstraction step by iodinanyl radicals. The energy of such a species might be considered to depend on the relative strengths of the I-H bond of **11** and the O-H bond of **10**. This oversimplified comparison neglects the I-O bond, or more precisely the three-center, four-electron (3-c, 4-e) nature of the H-I-O bond of **11**. A choice between structures **10** and **11** is not a priori simple, and conclusive experimental evidence bearing on this question is not yet available.

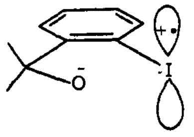
The question of the existence of a hydridoiodinane bears on the question of whether hydrogen abstraction by an iodinanyl radical occurs at iodine or at a heteroatom attached to iodine. Both Tanner[5] and Huyser[4] have suggested that hydrogen abstraction by $\mathrm{Ph\dot{I}Cl}$ (derived from **1**) occurs at iodine, although Breslow's[10] work with chloroiodinanes bound to steroids led him to suggest that abstraction occurs at a chlorine attached to iodine. Further work is necessary to answer the question of whether I-H iodinanes may be intermediates in these reactions.

**Bonding and Structure of the Iodinanyl Radical.** The iodinanyl radicals which we have postulated as the chain-carrying species for reactions of **2a-b** and of **3a** are analogous to those postulated for $C_6H_5\dot{I}Cl$[4,5a] and for $C_6H_5\dot{I}[O(CH_3)_3]$.[9] Neither ESR spectroscopic studies nor theoretical calculations have been performed on iodinanyl radicals. While the radical derived from **1** may be described by one of several models which utilize either a "bent" $\mathrm{Ph\dot{I}Cl}$ geometry or a linear $\mathrm{Ph\dot{I}Cl}$ geometry, the cyclic iodinanyl radicals of our study must necessarily be constrained to a geometry in which the C-I-O angle is $<180°$.

A most likely bonding scheme for the bent iodinanyl radicals of this study is that involving a two-center, three-electron (2-c, 3-e) I-O $\sigma$ bond[28] (i.e., **12**). The alternative formulation as $\pi$ radical **13** has only weak electrostatic O-I bonding in this case and hence seems to us less likely than **12**.



**12**



**13**

**Attempted Radical Fluorinations with Fluoroiodinane 2c.** Fluoroiodinane **2c** does not give benzylic fluorination of substituted toluenes, either upon irradiation or upon heating in the presence of a free-radical initiator. This lack of free-radical fluorinations, in contrast to the ease of reactions of **2a-b** with toluenes, is surprising, especially in light of the exothermic nature of the overall C-F bond formation. The two chain-carrying radicals in such a reaction would be the iodinanyl radical (**4**) and the benzyl radical, identical with those in the bromination and chlorination sequences. Although the bond dissociation energy of the I-F bond of **2c** is not known, it is expected to be at least 65-75 kcal/mol (the value calculated for the bond dissociation energy of apical I-F bonds in $IF_3$).[29] Since I-F bond cleavage in going from iodinane **2c** to iodinanyl radical **4** involves changes in both I-F and I-O bond strengths which are expected to weaken the I-O bond in **4**, we expect the I-F bond dissociation energy to be >65-75 kcal/mol, but probably still less than the C-F bond dissociation energy for benzyl fluoride ($\sim$104-108 kcal/mol).[30] If so, we may attribute our failure to observe fluorination to a transition-state effect, a high energy of activation for fluorine abstraction by benzyl radical, because this transition state resembles a very unfavored hypervalent bonding system, with the very electronegative fluorine atom in the central position. This results in the failure of step 5, pictured in Scheme I, and hence, does not lead to free-radical fluorinations.

## Conclusion

Chloro- and bromoalkoxyiodinanes give highly selective benzylic and allylic halogenations by a radical-chain process which involves iodinanyl radicals. The high yield and high selectivity of this process and the ease with which the iodinane is regenerated from the product alcohol suggest that iodinanes may be synthetically useful as allylic and benzylic chlorinating and brominating agents.

## Experimental Section

**Substituted Toluene Halogenations, General.** Benzene and toluenes, all of which are commercially available, were purified by standard literature methods,[31] and their purity was checked by 90-MHz $^1$H NMR spectroscopy. Fluoro-, chloro-, and bromoarylalkoxyiodinanes were prepared as previously described[24] and recrystallized prior to use. Dichlorophenyliodinane was prepared by the method of Lucas and Kennedy.[32] Other substrates and reagents were used without further purification.

**Initiation by Ultraviolet Radiation.** NMR sample tubes were filled with appropriate amounts of halogenation reagent, mixed toluenes, and benzene (solvent). The reagents were used in concentrations such that the halide products formed did not exceed 5% of total toluenes initially present, or 20% of the most reactive substrate.

Samples were degassed through three freeze-thaw cycles and sealed under vacuum. Reaction was initiated, in a stirred bath at 50.0 ± 0.1 °C, by use of a 275-W GE sun lamp. Reaction times varied from 15 to 60 min for completion, as indicated by sample decolorization.

**Analytical Method.** The relative reactivities of the $\alpha$ hydrogens of substituted toluenes toward various free-radical halogenating agents were determined by the competitive technique, using the integrated rate equation (eq 1) for the analysis.

$$k_{\mathrm{rel}} = \frac{\log\,[(A - X)/A]}{\log\,[(B - Y)/B]} \qquad (1)$$

Relative concentrations of benzyl halide products and of remaining toluenes were determined by integration of the areas of the $^1$H NMR peaks corresponding to methyl and to benzylic hydrogens. At least six integrals were run on every sample and results are precise to within ±3%.

**Chlorinations of 2,3-Dimethylbutane.** Reagent grade 2,3-dimethylbutane was used without further purification. The primary/tertiary selectivity ratio (on a per hydrogen basis) was calculated in the usual manner by comparison of the product distributions.

Reactions were carried out in sealed NMR tubes on mixtures which had been vacuum degassed by the freeze-thaw method. The sealed tubes were irradiated at 50.0 ± 0.1 °C with a 275-W GE sun lamp. The reactions were judged complete when the samples had become colorless.

**Chlorinations of *cis*- and *trans*-2-Butenes.** Samples of the appropriate iodinane (**2a** or **3a**) and a tenfold excess of *cis*- or *trans*-2-butene were vacuum degassed (three freeze-thaw cycles) and sealed. The samples, which were maintained at 40.0 ± 0.1 °C in a water bath, were irradiated with a 275-W GE sun lamp. The completion of reaction was indicated by decolorization of the initially yellow samples.

Ratios of allylic chlorination products were determined by integration of the $^1$H NMR spectra. Relative areas of methyl and methylene hydrogens of the two products were determined by at least six integrals, precise within ±3%. Peak positions were correlated with those reported by Ewing and Parry[33] for pure, authentic allylic chlorides. In addition, authentic allylic chlorides were prepared by the method of Walling and Thaler.[20] Amounts of other products, thought to be addition products, were established by $^1$H NMR spectroscopy to be present in amounts <10%. No measurable amounts of cis-trans isomerization were observed by $^1$H NMR spectroscopy (<5% limit of detectability).

Samples of *cis*- and of *trans*-1-chloro-2-butene were treated with excess iodo alcohol **9** to determine whether products were interconverted under our reaction conditions. No measurable amounts (<5%) of cis-trans isomerization were observed by $^1$H NMR spectroscopy under these conditions.

Test of *cis*- and of *trans*-2-butene stored in the dark with added iodinane (**2a** and **3a**) showed no decolorization of the yellow samples and no change in the $^1$H NMR spectra after 48 h. This is longer than the time (6–12 h) required for completion of the photoinitiated reactions.

**Reaction of 3b with Hydrogen Bromide.** A solution of **3b** (50 mg, 0.15 mmol) in 0.5 mL of $CCl_4$ was treated with excess anhydrous hydrogen bromide. The initially yellow solution immediately turned dark reddish brown, indicating the presence of bromine. The $^1$H NMR spectrum of the sample was identical with that of authentic 1-(2-iodophenyl)-1-methylethanol (**10**).[24] No signals attributable to **3b** were observed after addition of HBr was complete.

**Irradiation of 2c with Toluenes.** In a typical experiment, 11.5 mg (0.12 mmol) of toluene was irradiated with a 275-W GE sun lamp for 12 h in the presence of **2c** (50.0 mg, 0.12 mmol). The sample, which was evacuated (three freeze-thaw cycles) and sealed, was maintained at 50.0 ± 0.1 °C in a constant-temperature bath. The $^{19}$F NMR spectrum of the sample after 12 h showed no reaction.

A similar sample of *p*-xylene, with added 2,2′-azobisisobutyronitrile (1.0 mg), was warmed to 60 °C and irradiated for 15 h. No reaction was observed by $^{19}$F NMR spectroscopy.

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