In addition, starting from compound **1** (X = alkyl, H), various C-11 alkylprostaglandins and C-11 deoxyprostaglandins have been synthesized. By varying the
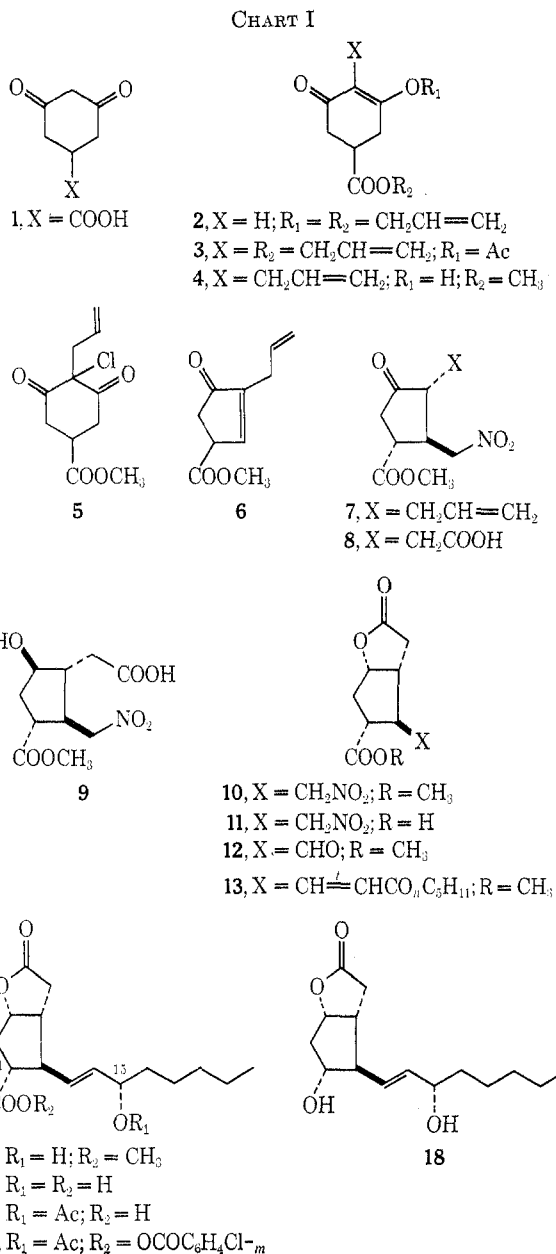
CHART I

1, X = COOH

2, X = H; R$_1$ = R$_2$ = CH$_2$CH=CH$_2$
3, X = R$_2$ = CH$_2$CH=CH$_2$; R$_1$ = Ac
4, X = CH$_2$CH=CH$_2$; R$_1$ = H; R$_2$ = CH$_3$

5

6

7, X = CH$_2$CH=CH$_2$
8, X = CH$_2$COOH

9

10, X = CH$_2$NO$_2$; R = CH$_3$
11, X = CH$_2$NO$_2$; R = H
12, X = CHO; R = CH$_3$
13, X = CH=CHCO$_n$C$_5$H$_{11}$; R = CH$_3$

14, R$_1$ = H; R$_2$ = CH$_3$
15, R$_1$ = R$_2$ = H
16, R$_1$ = Ac; R$_2$ = H
17, R$_1$ = Ac; R$_2$ = OCOC$_6$H$_4$Cl-*m*

18

type of Wittig reagent used, various side-chain analogs have also been prepared. Description of this work is in preparation.

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The Oxymercuration of *cis*- and *trans*-Di-*tert*-butylethylene.   Evidence for a π-Bridged Intermediate

Summary: The methoxymercuration of *cis*-di-*tert*-butylethylene proceeds by an anti addition without molecular rearrangement or carbon–carbon bond rotation providing evidence for a π-bridged intermediate.

Sir: The intermediacy of mercurinium ions in the oxymercuration reaction has been the subject of recent controversy. Arguments for[1] and against[2] the involvement of these mercury-bridged π complexes have recently appeared in the literature. Although kinetic studies[3] have not yet provided evidence for mercurinium ions under oxymercurating conditions, they have been observed in solution[4] and in the gas phase.[5] We now report convincing evidence for significant π bridging in the oxymercuration of the highly strained *cis*-di-*tert*-butylethylene (**1**). Our results also clearly demonstrate that alkene strain energy is not a dominant factor in the rate of oxymercuration of alkenes.

On the basis of theoretical calculations[6] and photoelectron spectroscopy,[7] **1** has been determined to be essentially a planar alkene with relief of steric repulsions of the *tert*-butyl groups being manifested by inplane angle distortion (C–C–*tert*-butyl bond angle, 136°). The ground-state energy of **1** is 10.2 kcal/mol[8] higher in energy than the relatively unstrained *trans*-di-*tert*-butylethylene (**2**). The difference in strain energy between **1** and **2** provides a unique opportunity to examine the question as to whether the steric repulsion between the *cis*-*tert*-butyl groups is sufficient to destabilize the π-bridged mercurinium ion by C$_1$–C$_2$ bond rotation affording a free carbonium ion.

Methoxymercuration of **1** with Hg(ClO$_4$)$_2$ in methanol solvent followed by Cl$^-$ treatment afforded *dl*-*threo*-3-(chloromercuri)-4-methoxy-2,2,5,5-tetramethylhexane (**3**)[9] by the preferred anti addition[10] (eq 1). The structural assignment of **3** was based on the vicinal H$_1$–H$_2$ coupling constant[11] ($J_{H_{1,2}}$ = 1.6 Hz) and on the nmr chemical-shift difference[12] of the methoxyl resonance in carbon tetrachloride and pyridine solvent. Methoxymercuration of **2** with Hg(ClO$_4$)$_2$ also afforded the threo isomer **3** by a syn addition to the double bond. This provides the first example of a syn addition to an unstrained alkene in the oxymercuration reaction and

(1)   D. J. Pasto and J. A. Gontarz, *J. Amer. Chem. Soc.*, **93**, 6902 (1971); R. D. Bach and R. F. Richter, *ibid.*, **94**, 4747 (1972), and references cited therein.

(2)   H. C. Brown and K.-T. Liu, *J. Amer. Chem. Soc.*, **93**, 7335 (1971).

(3)   J. Halpern and H. B. Tinker, *J. Amer. Chem Soc.*, **89**, 6427 (1967).

(4)   G. H. Olah and P. R. Clifford, *J. Amer. Chem Soc.*, **93**, 1261, 2320 (1971).

(5)   R. D. Bach, J. Gauglhofer, and L. Kevan, *J. Amer. Chem. Soc.*, **94**, 6860 (1972).

(6)   N. L. Allinger and J. T. Sprague, *J. Amer. Chem. Soc.*, **94**, 5734 (1972); E. H. Weibenga and E. Bowhuis, *Tetrahedron*, **25**, 453 (1969).

(7)   M. B. Robin, G. N. Taylor, N. H. Kuebler, and R. D. Bach, *J. Org. Chem.*, **38**, 1049 (1973).

(8)   J. D. Rockenfeller and F. D. Rossini, *J. Phys. Chem.*, **65**, 267 (1961).

(9)   The compound had mp 85.5–87°; ir (CCl$_4$) 1040 cm^{-1} (COC); nmr (CCl$_4$) 213.7 Hz (s, 3), δ 3.15 (d, 1, *J* = 1.6 Hz), 2.13 (d, 1, *J* = 1.6 Hz), 0.99 (s, 9).

(10)   W. Kitching, *Organometal. Chem. Rev.*, **3**, 61 (1968).

(11)   The *dl*-dichloride derived from anti addition of Cl$_2$ to **1** has a ^{13}C–H coupling constant of 0.8 Hz while the meso isomer has a coupling constant of 5.2 Hz: R. C. Fahey, *J. Amer. Chem. Soc.*, **88**, 4681 (1966).

(12)   R. F. Richter, J. C. Philips, and R. D. Bach, *Tetrahedron Lett.*, 4327 (1972).
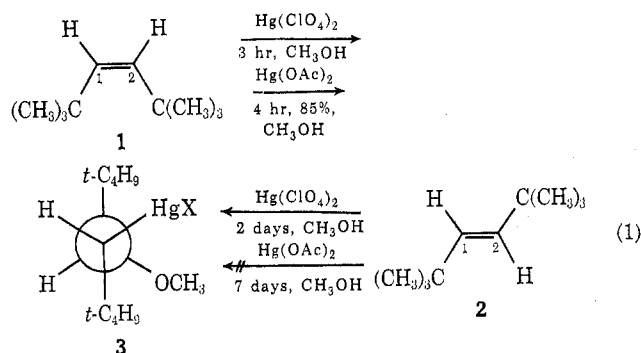
clearly demonstrates that enhanced reactivity is not a prerequisite for syn addition.

Since it is generally accepted that an increase in alkene ground-state energy due to bond angle strain will accelerate the rate of oxymercuration, in the absence of twist strain[13] effects, we were quite surprised to observe that the relative rate of methoxymercuration of 1 with mercuric acetate was 10^3 times *as slow as* the unstrained cyclohexene. Moreover, 2 did not exhibit a measurable reactivity toward $Hg(OAc)_2$ over a 7-day period.[14] This result is precisely the opposite to that which would be predicted on the basis of the relative rates of the chlorination of 1 and 2 where the relative rate ratio k_{trans}/k_{cis} had a value of 2.7.[11] Since both olefins are essentially planar,[7] steric effects must play the dominant role in the lack of reactivity and in the syn addition to 2.

Since the angle strain in 1 results from cisoid repulsion of the bulky *tert*-butyl groups, we thought that it would be of interest to measure the relative rate of methoxymercuration of cyclobutene where angle compression strain but no steric effects are involved. Again angle strain resulted in a decrease in relative rate and the methoxymercuration of cyclobutene was only 0.36 relative to cyclohexene despite the fact that the preferred anti addition was involved in both cases. Moreover, the relative rate of oxymercuration of norbornene, which affords a syn adduct, was only 4.5 times as fast as cyclohexene and, in fact, bicyclo[2.2.2]octene exhibited a relative rate of only 0.03.[15] *trans*-Cyclooctene, which has torsional strain (the double bond is twisted ~20° out of plane[7] resulting in 9.2 kcal/mol of strain energy relative to the cis isomer), methoxymercurates at a rate of only 10.1 times as fast as cyclohexene. Indeed, 1-octene exhibits a rate of methoxymercuration comparable to that of *trans*-cyclooctene and is 9.5 times as fast as that of cyclohexene. However, the comparatively faster rate (10^4) of methoxymercuration of *trans*-cyclooctene *via* a syn mode of addition relative to the anti mode of addition to 1, which has a comparable

strain energy, is indeed striking and, therefore, demands a reevaluation of the effects of strain energy on the rate of oxymercuration reactions with alkenes.

Several factors argue against a carbonium ion mechanism in the oxymercuration reaction. For example, only 1,2 addition to 1,3-dienes has been observed in the absence of structural rearrangement or conjugate addition. Theoretical calculations[5,17] also suggest that mercurinium ions prefer to be planar in the absence of steric strain and are stabilized principally by $\sigma-\pi$ conjugation without development of significant charge at carbon. The lack of carbonium ion rearrangements during the syn oxymercuration of 2 is consistent with this hypothesis. Moreover, bromination of 2 in methanol solvent, where an appreciable charge at carbon develops,[17] afforded only rearranged products with no methoxy bromination being detected. Therefore, stereospecific anti addition to 1, in addition to the absence of olefin isomerization or molecular rearrangements due to carbonium ion formation, strongly suggests that the extent of π bridging in the transition state is comparable to or greater than the 10.2-kcal/mol strain energy in 1.

Further corroboration for the mercurinum ion stability comes from deoxymercuration studies. It may be inferred from Kreevoy's kinetic data[18] on deoxymercuration that the enthalpy of activation for a syn deoxymercuration is ~5 kcal/mol higher than the anti deoxymercuration. In support of this, oxymercuration and deoxymercuration of *cis*- and *trans*-stilbene[19] has been shown to be completely stereospecific (the ground-state energy difference between the isomeric olefins is 4.5 kcal/mol). Deoxymercuration of 3, with concentrated HCl, afforded exclusively the trans isomer 2 which is compelling evidence for an unprecendented syn deoxymercuration in an acyclic system. Thus, a semiquantitative limit to steric inhibition for the preferred trans deoxymercuration reaction may now be placed between 4.5 and 10.2 kcal/mol.

Thus, it may be concluded that the oxymercuration of 1 proceeds *via* a bridged mercurinium ion intermediate. The relative rates observed provide dramatic evidence that significant relief of strain in the transition state for oxymercuration is not attained. These results are, therefore, consistent with the formation of an olefin π complex with subsequent attack by solvent in the rate-limiting step.

(13) T. G. Traylor, *Accounts Chem. Res.*, **2**, 152 (1969).

(14) This result precludes the possibility that 1 is isomerized to 2 prior to oxymercuration with $Hg(OAc)_2$. Control experiments and the nmr spectrum of the reaction mixture have also established that isomerization of 1 is not occurring under the reaction conditions.

(15) Similar observations have been made in the hydroxymercuration of these alkenes: H. C. Brown and P. J. Geohegan, *J. Org. Chem.*, **37**, 1937 (1972). Control experiments have established that alkene exchange reactions are slow under our experimental conditions. We have shown that olefin exchange reactions of oxymercurials are quite facile and relative rate studies must distinguish between the kinetic and thermodynamic products.[16]

(16) R. D. Bach, R. N. Brummel, and R. F. Richter, *Tetrahedron Lett.*, 2879 (1971).

(17) R. D. Bach and H. F. Henneike, *J. Amer. Chem. Soc.*, **92**, 5589 (1970); R. D. Bach and P. A. Scherr, *ibid.*, **94**, 220 (1972).

(18) M. M. Kreevoy, J. W. Gilje, L. T. Ditsch, W. Batorewicz, and M. A. Turner, *J. Org. Chem.*, **27**, 726 (1962).

(19) G. F. Wright, *Ann. N. Y. Acad. Sci.*, **65**, 436 (1957); M. M. Kreevoy, private communication.

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