Journal of Organometallic Chemistry, 435 (1992) 357–376
Elsevier Sequoia S.A., Lausanne
JOM 22714

An X-ray crystallographic and high field NMR study of [7-dehydrocholesteryl acetate]Fe(CO)$_3$: synthesis of a B-ring cyclohexadienyl cationic complex

Richard E. Perrier, Christopher S. Frampton and Michael J. McGlinchey
Department of Chemistry, McMaster University, Hamilton, Ontario L8S 4M1 (Canada)

(Received September 10, 1991)

Abstract

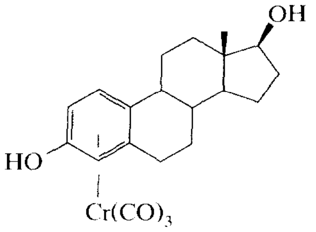
(7-Dehydrocholesteryl acetate)Fe(CO)$_3$ crystallizes in the triclinic space group $P1$ with $a = 11.238(3)$, $b = 14.718(3)$, $c = 10.899(2)$ Å, $\alpha = 104.83(2)$, $\beta = 113.77(2)$, $\gamma = 96.75(2)°$, $V = 1544.2(6)$ Å^3, for $Z = 2$, and $R_1 = 0.0572$, $R_2 = 0.0668$ for 3135 reflections with $I > 3\sigma(I)$. The B ring of the complex adopts an envelope conformation quite different from that of uncomplexed steroidal B-ring dienes which have half-chair structures. The organometallic fragment renders the α-hydrogen attached to C(9) inaccessible to an approaching triphenylmethyl cation and so prevents hydride abstraction and formation of metal complexed B-ring steroidal cyclohexadienyl cations. However, the corresponding 9,11-dehydroergosteryl complex can be protonated at the 11 position to yield a B-ring cationic complex. The complexes are characterized by their high field ^{1}H and ^{13}C NMR spectra.

Introduction

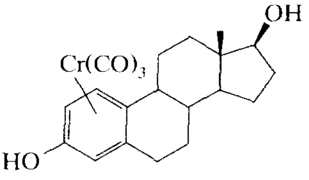
Steroidal systems offer a multitude of potential sites to which transition metals may be attached [1–3]. A primary goal of previous studies in this area was the incorporation of metal carbonyl fragments as bio-organometallic labels in hormonal steroids [4,5]. It has been shown that the very intense metal carbonyl ν(CO) infrared stretching vibrations can be used to assay hormonal receptor sites; this novel technique promises to be an invaluable tool for the early detection of breast cancer [6,7]. In this connection we have previously made use of high field two-dimensional NMR spectroscopy to distinguish the α- and β-diastereomers of Cr(CO)$_3$ derivatives of estradiol, **1a** and **1b** [8], and of related molecules, such as the methyl podocarpate complexes **2a** and **2b** [9]. In these cases, as with the (C$_5$H$_5$)Ru complexes of estrone, **3a** and **3b**, the metal was bonded in an η^6 manner to the A-ring of the steroid [10]. In contrast, treatment of 17-keto steroids

---

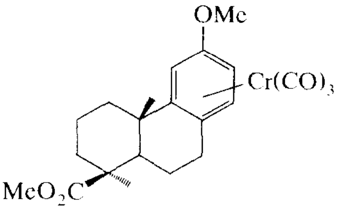
Correspondence to: Dr. M.J. McGlinchey.



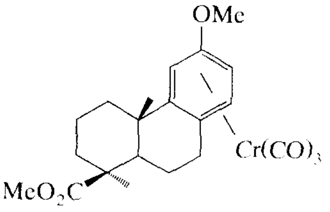
(**1**α)



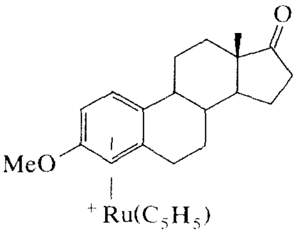
(**1**β)



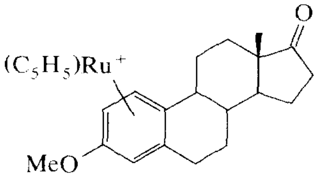
(**2**α)



(**2**β)

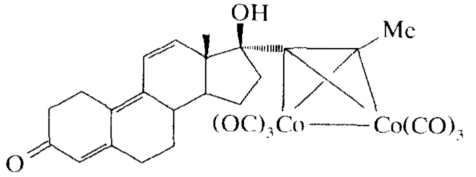


(**3**α)

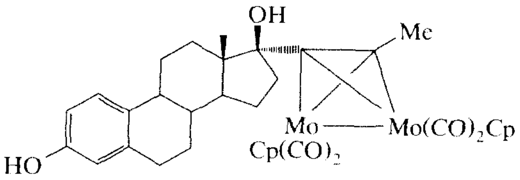


(**3**β)

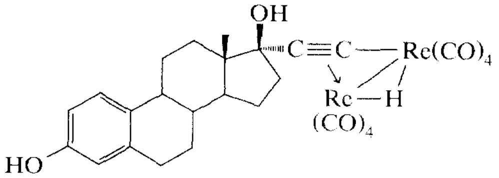
with an acetylide anion leads to 17α-alkynyl systems which are widely used as contraceptives or abortifactants; these yield cobalt, molybdenum or rhenium clusters such as **4**, **5** and **6** [11–14].



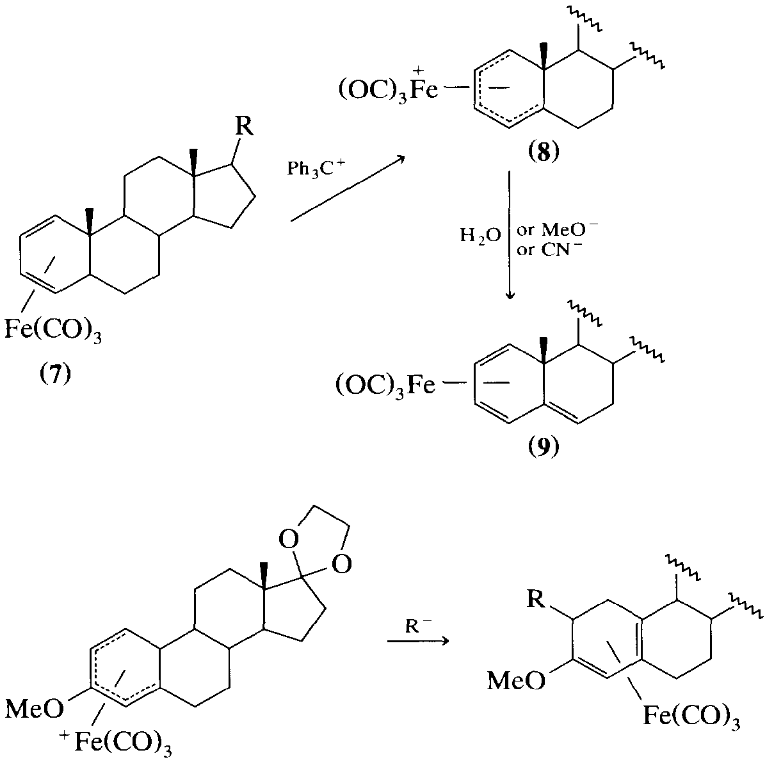
(**4**)



(**5**)



(**6**)



Scheme 1. Reactions of nucleophiles with A ring cationic complexes.

Organometallic derivatives have also been described in which an $Fe(CO)_3$ fragment was used to protect the diene unit in the B-ring of ergosterol and related plant steroids; this permitted the facile manipulation of the C(22)–C(23) double bond [15,16]. Likewise (η^3-allyl)palladium and η^6-$Cr(CO)_3$ groups have also been exploited for synthetic purposes [17–20]. Moreover, the potential of inorganic salts, such as $RhCl_3$, or of organometallic reagents, *e.g.*, $Cr(CO)_6$, to bring about the selective migration of double bonds in ergosterol has been reported [21,22].

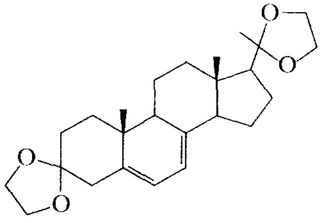
Of particular relevance to the present study are the elegant contributions of Birch [23] and Pearson [24,25] who have used the $Fe(CO)_3$ moiety not only to stabilize cyclohexadienyl cations but also to control the site of attack by incoming nucleophiles. In the steroidal series, Alper has prepared an A-ring cyclohexadienyl-$Fe(CO)_3$ cation by treatment of the precursor cholesta-2,4-diene complex **7** with the triphenylmethyl cation. However, attempts to incorporate new functional groups by addition of nucleophiles to the cation **8** led instead to deprotonation and generation of the triene complex **9** [26]. Nevertheless, it has been reported that in some cases it is possible to obtain A-ring substituted products [27], as in Scheme 1. Attempts to introduce angular groups, *i.e.*, at the C(10) position were unsuccessful.

We now describe the synthesis of some B-ring cyclohexadienyl–$Fe(CO)_3$ complexes together with an X-ray crystal structure of [7-dehydrocholesteryl acetate]$Fe(CO)_3$.

Results and discussion

Structure of [7-dehydrocholesteryl acetate]Fe(CO)$_3$

In our previous studies of B-ring complexed steroidal systems, we have reported detailed NMR studies of ergosteryl acetate and 7-dehydrocholesteryl acetate together with their Fe(CO)$_3$ and Rh(acac) derivatives [1]. In these investigations we noted that the chemical shifts of protons situated in the vicinity of metal carbonyl linkages were affected quite appreciably by the diamagnetic anisotropy of the linear M=C=O fragments. Indeed, this had been the basis on which the α- and β-Cr(CO)$_3$ complexes of estradiol had been differentiated [8]. However, it is also known that the geometry of steroids is rather sensitive to the steric requirements of the substituents [28] and that this molecular flexibility is often most evident in the conformation adopted by the B ring. We were unaware of any X-ray crystallographic data on the free ligands ergosterol or 7-dehydrocholesterol or on simple derivatives thereof. Apparently, these molecules crystallize as very thin platelets quite unsuitable for diffraction studies. However, the related molecule **10** which bears ethylene-dioxy substituents at C(3) and at C(20) has been characterized in the solid state [29]. The X-ray crystal structure of [7-dehydrocholesteryl acetate]Fe(CO)$_3$ (**11**) was undertaken to allow comparisons to be drawn between a non-complexed diene such as **10** and a B-ring complexed Fe(CO)$_3$ derivative.



(**10**)

The complex **11** crystallizes with two independent molecules in the unit cell such that the orientation of the Fe(CO)$_3$ moiety relative to the diene system is very slightly different in the two cases. The crystallographic data are given in Tables 1–5. Figure 1 shows a view of **11** clearly indicating the point of attachment of the tricarbonyl unit to the diene carbons at C(5), C(6), C(7) and C(8). A view of the unit cell appears as Fig. 2. Of particular significance is the folded envelope conformation adopted by the B ring of the complexed steroid, as shown in Fig. 3.

An extremely useful method of describing the conformations of steroidal rings has been developed by Duax [28,30]. For diene systems such as **10** or **11**, one can envisage two extreme situations: firstly, a half-chair conformation in which carbons C(5), C(6), C(7) and C(8) are coplanar while C(10) and C(9) are symmetrically positioned, respectively, above and below this plane (Fig. 4(a)). The second structure (Fig. 4(b)) is the envelope conformation in which both C(10) and C(9) lie above the aforementioned plane.

In order to quantify these conformational differences, one may utilize the asymmetry parameters ΔC_2 and ΔC_s which are calculable from the endocyclic torsional angles [28,30]. These parameters provide a measure of the deviation from an ideally symmetric conformation; *i.e.*, low values of ΔC_2 or ΔC_s indicate a high degree of symmetry about the defined two-fold rotation axis or mirror plane,

Table 1

Crystal data for [$C_{29}H_{46}O_2Fe(CO)_3$]

Formula	$C_{32}H_{46}O_5Fe$
F.W.	565.55
System	Triclinic
Space group	$P1$ (no. 1)
a (Å)	11.238(3)
b (Å)	14.718(3)
c (Å)	10.899(2)
α (°)	104.83(2)
β (°)	113.77(2)
γ (°)	96.75(2)
V (Å^3)	1544.2(6)
Z	2
D_c (D_m) (g cm^{-3})	1.22 (1.204)
F(000)	606.81(606)
μ(Mo-K_α) (cm^{-1})	5.42
Final R_1, R_2 [a]	0.0572, 0.0668
Weighting scheme	$w = (\sigma^2 F + 0.008126F^2)^{-1}$
No. of reflections collected	4483
No. with $I > 3\sigma$	3135
Error in observation of unit weight [b]	0.8961
Highest peak (e Å^{-3}); location	0.54; 0.80, 0.12, −0.13
Lowest peak (e Å^{-3})	−0.41

[a] $R_1 = \Sigma \| F_o| - |F_c\| / \Sigma |F_o|$; $R_2 = (\Sigma w(|F_o| - |F_c|)^2/\Sigma w F_o^2)^{1/2}$. [b] $S(\Sigma w(|F_o| - |F_c|)^2/(m-n))^{1/2}$. m = no. of reflections, n = no. of variables.

respectively. Thus, the half-chair conformer has local C_2 symmetry about an imaginary axis drawn through the mid-points of the C(6)–C(7) and C(9)–C(10) bonds, while the envelope structure has a pseudo mirror plane containing these same two mid-points. The relevant asymmetry parameters are defined as follows:

$$\Delta C_2 = \{[(\phi_{6-5} - \phi_{7-8}) + (\phi_{5-10} - \phi_{8-9})]/2\}^{1/2}$$

$$\Delta C_s = \{[(\phi_{6-5} + \phi_{7-8}) + (\phi_{5-10} + \phi_{8-9})]/2\}^{1/2}$$

where ϕ_{6-5}, for example, is the dihedral angle within the B ring, *i.e.*, the angle C(7)–C(6)–C(5)–C(10). Thus, for the idealized conformers, these numerical values will be zero. In the case at hand, the values of ΔC_s for the two independent molecules of the iron complex **11** are 19° and 16°; in contrast, the corresponding ΔC_s for the non-complexed bis-ketal **10** is 45°. For comparison, the analogous values of ΔC_2 are 84° and 80° for the two molecules of **11** but only 4° for **10**. These results show unequivocally that the B ring in the non-complexed steroidal diene **10** is an almost perfect half-chair while in the $Fe(CO)_3$ complex, the B ring has become an envelope. The relatively low values (ranging from ~ 2° to ~ 9°) of the asymmetry parameters for both the A and C rings of **11** indicate that these adopt slightly distorted chairs, while the D ring is of the normal envelope type. Although the geometry of the B ring of **11** is similar to that observed in other cyclic diene $Fe(CO)_3$ complexes, in which a fold angle of ~ 40° is typical [31–33], this is a most

Table 2

Positional parameters ($\times 10^4$) and U_{eq} ($Å^2 \times 10^4$) for $[(C_{29}H_{46}O_2Fe(CO)_3]$, with estimated standard deviations in parentheses

Atom	*x*	*y*	*z*	U_{eq} [a]
Molecule 1				
Fe(1)	3564(2)	9300(1)	1031(2)	496
C(91)	5037(0)	9923(0)	2769(0)	908
O(91)	5958(0)	10376(0)	3822(0)	1396
C(92)	4619(0)	8773(0)	452(0)	702
O(92)	5425(0)	8445(0)	127(0)	938
C(93)	3402(0)	10245(0)	376(0)	703
O(93)	3360(0)	10923(0)	−34(0)	895
C(1)	234(12)	9073(8)	−2219(9)	581
C(2)	270(13)	8361(10)	−3532(12)	776
C(3)	1556(13)	8068(8)	−3111(11)	693
C(4)	1822(12)	7607(8)	−2035(10)	585
C(5)	1820(11)	8247(6)	−677(11)	507
C(6)	2332(11)	7969(8)	581(10)	492
C(7)	2432(10)	8668(6)	1848(9)	384
C(8)	1991(9)	9479(6)	1656(10)	351
C(9)	778(10)	9440(6)	336(9)	419
C(10)	555(10)	8621(8)	−958(10)	461
C(11)	−480(9)	9397(8)	649(9)	435
C(12)	−216(11)	10220(9)	2010(10)	560
C(13)	991(9)	10218(6)	3269(10)	367
C(14)	2183(9)	10362(8)	2970(10)	469
C(15)	3441(13)	10574(10)	4387(11)	749
C(16)	2963(10)	11147(9)	5501(12)	590
C(17)	1493(9)	11111(6)	4672(10)	411
C(18)	787(11)	9276(6)	3648(10)	450
C(19)	−633(11)	7758(8)	−1472(12)	545
C(20)	804(10)	11157(8)	5642(11)	455
C(21)	−778(12)	11056(10)	4884(13)	755
C(22)	1465(11)	12105(8)	6900(10)	552
C(23)	943(11)	12210(6)	8033(10)	462
C(24)	1646(12)	13109(8)	9277(10)	557
C(25)	1095(12)	13324(8)	10326(11)	595
C(26)	1885(13)	14306(9)	11487(11)	730
C(27)	1227(13)	12558(10)	11041(13)	711
O(29)	1533(10)	7353(6)	−4350(8)	792
C(30)	2340(10)	7488(9)	−4897(9)	489
O(30)	3167(9)	8235(6)	−4412(11)	829
C(31)	2117(13)	6670(10)	−6082(11)	804
Molecule 2				
Fe(2)	4532(0)	5086(0)	−2071(0)	388
C(91)	5041(0)	6263(0)	−2264(0)	648
O(91)	5340(0)	6943(0)	−2448(0)	809
C(92)	3389(0)	5396(0)	−1306(0)	508
O(92)	2648(0)	5581(0)	−922(0)	708
C(93)	3091(0)	4562(0)	−3776(0)	710
O(93)	2116(0)	4219(0)	−4792(0)	884
C(1)	7997(11)	6691(8)	782(11)	587
C(2)	7967(12)	7030(9)	2221(11)	698
C(3)	6559(11)	6705(8)	1993(10)	519
C(4)	6051(11)	5607(8)	1380(10)	506

Table 2 (continued)

Atom	x	y	z	U_{eq} [a]
Molecule 2				
C(5)	6142(0)	5226(0)	−28(0)	445
C(6)	5392(10)	4219(6)	−892(10)	444
C(7)	5383(10)	3924(6)	−2242(10)	420
C(8)	6064(9)	4583(6)	−2630(9)	321
C(9)	7411(9)	5309(6)	−1486(9)	351
C(10)	7506(9)	5579(6)	52(9)	339
C(11)	8625(10)	4967(9)	−1615(11)	546
C(12)	8468(10)	4753(9)	−3151(11)	600
C(13)	7162(9)	3978(6)	−4243(10)	406
C(14)	5968(10)	4352(6)	−4044(9)	420
C(15)	4725(9)	3721(8)	−5405(10)	492
C(16)	5174(11)	3389(10)	−6525(11)	613
C(17)	6710(11)	3768(8)	−5857(9)	478
C(18)	7163(11)	3009(6)	−3885(11)	487
C(19)	8509(11)	5055(9)	949(11)	594
C(20)	7433(10)	3124(8)	−6495(10)	490
C(21)	8953(10)	3609(10)	−5824(12)	691
C(22)	6746(12)	2881(9)	−8192(11)	580
C(23)	7129(12)	2082(10)	−8866(12)	682
C(24)	6544(13)	1857(9)	−10548(12)	696
C(25)	6799(13)	983(11)	−11271(13)	840
C(26)	5914(13)	31(11)	−11595(16)	992
C(27)	7098(15)	1003(13)	−12404(16)	1070
O(29)	6694(8)	7033(6)	3443(6)	609
C(30)	5557(13)	7222(11)	3495(12)	769
O(30)	4469(10)	7050(9)	2547(10)	901
C(31)	5933(13)	7727(12)	5217(12)	912

[a] $U_{eq} = \frac{1}{3}(U_{11} + U_{22} + U_{33} + 2U_{23}\cos\alpha + 2U_{13}\cos\beta + 2U_{12}\cos\gamma)$.

unusual feature in a steroidal system. Overall, one can conclude that **11** behaves as a heavily substituted (cyclohexadiene)$Fe(CO)_3$ complex.

A (cyclohexadienyl)$Fe(CO)_3$ complex of a steroidal B-ring

Conventional routes to (cyclohexadienyl)metal cations involve the use of the triphenylmethyl cation to abstract hydride from a diene precursor [23–26]. However, in **11** or the analogous [ergosteryl acetate]$Fe(CO)_3$ complex (**12**), such a process is impossible. There is no available hydrogen situated in an exo position and, as shown clearly in Fig. 5, the H(9α) site is sterically inaccessible because the bulky organometallic tripod blocks the α-face of the steroid B ring.

An alternative approach would be the protonation of a suitable triene, in this case the 5,7,9(11)-triene. To this end, ergosteryl acetate was first treated with mercuric acetate to generate the desired triene **13**; as shown in Scheme 2, reaction of **13** with (benzylideneacetone)$Fe(CO)_3$ gave the complex **14** and subsequent addition of HPF_6 led to the cation **15** in 24% overall yield.

This sequence of reactions is easily followed by ^1H and ^{13}C NMR spectroscopy and full data for **13**, **14** and **15** are collected in Tables 6 and 7. The olefinic sections of the 500 MHz ^1H spectra are shown in Fig. 6 and show clearly how the H(6) and H(7) protons as well as H(11) are noticeably shielded upon complexation of the

Table 3

Selected bond lengths (Å) for 7-dehydrocholesteryl acetate–Fe(CO)$_3$ with estimated standard deviations in parentheses

Bond	Molecule 1	Molecule 2
Fe coordination		
Fe–C91	1.843(1)	1.851(1)
Fe–C92	1.725(2)	1.832(2)
Fe–C93	1.714(2)	1.793(2)
Fe–C5	2.139(8)	2.169(8)
Fe–C6	2.077(11)	2.084(11)
Fe–C7	2.081(13)	2.060(11)
Fe–C8	2.155(12)	2.192(11)
C91–O91	1.149(0)	1.111(0)
C92–O92	1.206(0)	1.103(0)
C93–O93	1.192(0)	1.135(0)
Steroidal skeleton		
C1–C2	1.561(18)	1.535(19)
C1–C10	1.608(17)	1.545(14)
C2–C3	1.483(21)	1.497(18)
C3–C4	1.448(18)	1.519(15)
C3–O29	1.473(15)	1.466(14)
C4–C5	1.539(17)	1.542(12)
C5–C6	1.444(16)	1.465(9)
C5–C10	1.529(17)	1.519(11)
C6–C7	1.449(15)	1.420(17)
C7–C8	1.377(15)	1.414(17)
C8–C9	1.514(12)	1.551(10)
C8–C14	1.586(14)	1.446(15)
C9–C10	1.509(14)	1.577(15)
C9–C11	1.581(17)	1.553(17)
C10–C19	1.531(15)	1.588(16)
C11–C12	1.547(14)	1.553(17)
C12–C13	1.492(13)	1.541(12)
C13–C14	1.505(17)	1.580(17)
C13–C17	1.577(12)	1.554(14)
C13–C18	1.561(16)	1.573(17)
C14–C15	1.540(13)	1.527(10)
C15–C16	1.607(20)	1.493(18)
C16–C17	1.517(14)	1.541(15)
C17–C20	1.535(18)	1.531(18)
C20–C21	1.599(16)	1.549(15)
C20–C22	1.528(13)	1.609(14)
C22–C23	1.550(19)	1.428(20)
C23–C24	1.478(12)	1.603(17)
C24–C25	1.491(20)	1.450(21)
C25–C26	1.529(14)	1.488(22)
C25–C27	1.514(20)	1.410(27)
C30–O29	1.293(18)	1.466(19)
C30–O30	1.191(14)	1.184(14)
C30–C31	1.434(16)	1.680(18)

Table 4

Selected bond angles (°) for [7-dehydrocholesteryl acetate] $Fe(CO)_3$, with estimated standard deviations in parentheses

Angle	Molecule 1	Molecule 2
Fe coordination		
Fe-C91-O91	174.6(1)	176.3(1)
Fe-C92-O92	175.8(1)	175.9(1)
Fe-C93-O93	176.6(1)	173.9(1)
C91-Fe-C92	87.8(1)	99.0(1)
C91-Fe-C93	99.5(1)	97.2(1)
C91-Fe-C5	162.2(4)	101.4(4)
C91-Fe-C6	122.2(3)	138.6(3)
C91-Fe-C7	95.0(2)	127.9(3)
C91-Fe-C8	99.4(2)	89.3(3)
C92-Fe-C93	103.2(1)	88.0(1)
C92-Fe-C5	92.2(4)	92.9(4)
C92-Fe-C6	93.2(4)	98.1(4)
C92-Fe-C7	125.0(3)	131.7(4)
C92-Fe-C8	161.5(3)	168.0(3)
C93-Fe-C5	97.9(4)	161.0(4)
C93-Fe-C6	135.8(3)	120.8(2)
C93-Fe-C7	130.1(3)	95.8(2)
C93-Fe-C8	92.5(3)	99.5(2)
C5-Fe-C6	40.0(4)	40.2(2)
C5-Fe-C7	70.5(4)	69.5(2)
C5-Fe-C8	75.8(4)	76.9(2)
C6-Fe-C7	40.8(4)	40.1(5)
C6-Fe-C8	68.6(4)	70.0(5)
C7-Fe-C8	37.9(4)	38.7(4)
Steroidal skeleton		
C1-C2-C3	110.9(9)	108.8(8)
C1-C10-C5	110.2(11)	109.3(8)
C1-C10-C9	108.2(9)	109.3(9)
C1-C10-C19	106.9(8)	110.6(7)
C2-C1-C10	110.9(10)	112.9(11)
C2-C3-C4	113.7(13)	111.7(11)
C2-C3-O29	109.8(8)	102.7(7)
C3-C4-C5	112.7(10)	110.0(10)
C3-O29-C30	124.6(9)	113.3(8)
C4-C3-O29	106.0(10)	109.0(10)
C4-C5-C6	118.5(10)	114.9(7)
C4-C5-C10	113.5(8)	114.9(5)
C4-C5-Fe	123.0(9)	122.6(4)
C5-C6-C7	114.7(10)	113.4(9)
C5-C6-Fe	72.3(6)	73.0(5)
C5-C10-C9	110.1(7)	110.4(5)
C5-C10-C19	108.4(9)	107.5(8)
C6-C5-C10	115.2(12)	118.3(6)
C6-C5-Fe	67.7(5)	66.8(4)
C6-C7-C8	115.1(9)	120.0(8)
C6-C7-Fe	69.5(7)	70.9(7)
C7-C6-Fe	69.7(6)	69.1(6)
C7-C8-C9	122.8(7)	119.5(8)
C7-C8-C14	121.0(9)	122.0(7)
C7-C8-Fe	68.1(7)	65.6(6)

Table 4 (continued)

Angle	Molecule 1	Molecule 2
Steroidal skeleton		
C8–C7–Fe	74.0(7)	75.7(6)
C8–C9–C10	112.1(9)	112.3(9)
C8–C9–C11	108.2(9)	111.2(8)
C8–C14–C15	117.3(10)	124.7(10)
C8–C14–C13	110.2(7)	116.3(8)
C9–C8–C14	109.7(9)	112.3(9)
C9–C8–Fe	106.0(8)	105.1(6)
C9–C10–C19	115.2(11)	109.5(9)
C9–C11–C12	112.5(7)	111.3(8)
C10–C5–Fe	111.6(6)	111.2(4)
C10–C9–C11	113.2(8)	115.0(8)
C11–C12–C13	111.3(10)	111.4(10)
C12–C13–C14	108.2(10)	107.1(8)
C12–C13–C17	116.2(9)	119.5(10)
C12–C13–C18	111.9(8)	109.9(8)
C13–C14–C15	106.8(10)	103.5(8)
C13–C17–C16	103.9(9)	103.3(10)
C13–C17–C20	120.6(8)	115.6(9)
C14–C13–C17	100.0(7)	102.4(3)
C14–C13–C18	112.6(10)	106.1(10)
C14–C15–C16	100.9(10)	107.2(8)
C15–C16–C17	107.5(8)	108.8(7)
C16–C17–C20	109.6(9)	115.8(8)
C17–C13–C18	107.5(9)	110.7(8)
C17–C20–C21	109.9(9)	111.5(8)
C17–C20–C22	115.3(9)	109.5(9)
C20–C22–C23	115.4(10)	111.1(10)
C21–C20–C22	108.6(10)	110.8(10)
C22–C23–C24	114.4(10)	112.8(11)
C23–C24–C25	117.7(11)	113.5(13)
C24–C25–C26	110.8(11)	118.2(15)
C25–C25–C27	109.3(11)	117.1(15)
C26–C25–C27	107.5(9)	111.4(12)
O29–C30–O30	120.4(11)	128.9(13)
O29–C30–C31	113.3(10)	107.4(9)
O30–C30–C31	126.3(13)	123.3(15)

iron tricarbonyl moiety to the C(5)–C(6)–C(7)–C(8) diene system in **14**. The protonation of **14** to yield the cation **15** has the expected effect of generating an sp^3 center at C(11) and so moves the ^{13}C resonance position of this carbon from δ 115.5 in **14** to δ 23.4 in **15**; concomitantly, the olefinic H(11) at δ 5.0 in **14** is replaced by a pair of methylene resonances at δ 1.98 and δ 1.68 in **15**. As shown in Fig. 5, the chemical shifts of H(22) and H(23) are almost unaffected by these transformations. Previous ^1H NMR data on (cyclohexadienyl)Fe(CO)$_3$ cations [34–36] would lead one to assign the remaining two alkene protons, namely H(6) and H(7), such that the more deshielded of the two is the one bonded to a carbon which bears (at least formally) a partial positive charge. That is, one can write canonical forms that place positive charge at the C(5), C(7) and C(9) centers. This assignment was confirmed by a combination of NMR techniques. The two-dimen-

Table 5

Endocyclic torsional angles (°) for [7-dehydrocholesteryl acetate] $Fe(CO)_3$

Angle	Molecule 1	Molecule 2
Fe coordination		
O91-C91-Fe-C5	−168.1	127.5
O91-C91-Fe-C6	−166.1	109.0
O91-C91-Fe-C7	−133.5	54.7
O91-C91-Fe-C8	−95.6	51.0
O92-C92-Fe-C5	−171.6	177.6
O92-C92-Fe-C6	−131.6	−142.2
O92-C92-Fe-C7	−104.0	−117.5
O92-C92-Fe-C8	−123.1	−150.9
O93-C93-Fe-C5	−160.4	68.1
O93-C93-Fe-C6	−175.1	72.9
O93-C93-Fe-C7	−128.5	106.4
O93-C93-Fe-C8	123.6	145.3
Steroidal skeleton		
C1-C2-C3-C4	58.2	60.8
C2-C3-C4-C5	−56.9	−57.1
C3-C4-C5-C10	52.5	51.7
C4-C5-C10-C1	−48.4	−49.1
C5-C10-C1-C2	49.3	52.4
C5-C6-C7-C8	1.7	0.3
C6-C7-C8-C9	38.0	36.6
C7-C8-C9-C10	−29.0	−28.5
C8-C9-C10-C5	−16.2	−11.9
C8-C14-C13-C12	−63.4	−55.5
C8-C9-C11-C12	52.5	53.0
C9-C10-C5-C6	53.8	49.5
C9-C8-C14-C13	62.7	53.5
C9-C11-C12-C13	−55.4	−57.8
C10-C1-C2-C3	−53.6	−58.8
C10-C5-C6-C7	−47.4	−45.1
C11-C9-C8-C14	−54.8	−50.7
C11-C12-C13-C14	60.0	55.5
C13-C14-C15-C16	−32.9	−24.9
C13-C17-C16-C15	21.1	21.1
C14-C15-C16-C17	6.0	2.6
C14-C13-C17-C16	−40.5	−35.4
C15-C14-C13-C17	46.1	37.4
C16-C17-C20-C22	60.7	52.9

sional COSY experiment reveals a cross-peak relating the protons at C(4) with that at C(6); this interaction is mediated by the long-range vinylic coupling. The H(6) peak at δ 5.53 is of course coupled to the H(7) resonance at δ 6.85. With these assignments in hand, the ^1H–^{13}C shift-correlated experiment leads to an unambiguous attribution of the C(6) and C(7) positions. The entire set of ^1H and ^{13}C assignments were obtained from these two-dimensional spectra and are collected in Tables 6 and 7.

The chemistry of the cation **15** has been investigated in a preliminary manner. The addition of nucleophiles such as methoxide and cyanide led only to proton

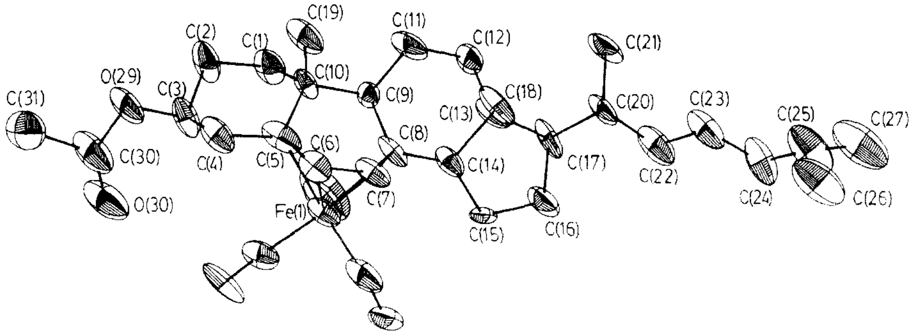


Fig. 1. View of (7-dehydrocholesteryl acetate)tricarbonyliron (**11**).

abstraction and regeneration of the triene complex **14**. Treatment with the relatively soft nucleophile thiocyanate had the same result. Examination of molecular models revealed that a nucleophile attacking the β-face of the B ring at either terminus of the pentadienyl system would encounter severe steric problems because of the methyl attached at C(10). However, it was noted that nitrosoarenes can attack the central carbon, *i.e.* C(7), *via* a complex redox mechanism to generate a nitroxide radical **16** which undergoes hydrogen migration yielding the conjugated diene **17**, as depicted in Scheme 3. These reactions were monitored by ESR spectroscopy and have been fully described elsewhere [37].

To conclude, the X-ray crystal structure of [7-dehydrocholesteryl acetate]Fe(CO)$_3$ (**11**) reveals that the steroidal B ring undergoes a marked conformational change from a regular half-chair to an envelope upon complexation. For steric reasons, the 9α-hydrogen in **11** is inaccessible to hydride abstracting agents and so does not yield the cyclohexadienyl cation **15**. However, dehydrogenation of either 7-dehydrocholesteryl acetate or ergosteryl acetate to the corresponding 5,7,9-triene leads to the required cation *via* protonation of the triene-Fe(CO)$_3$ molecules.

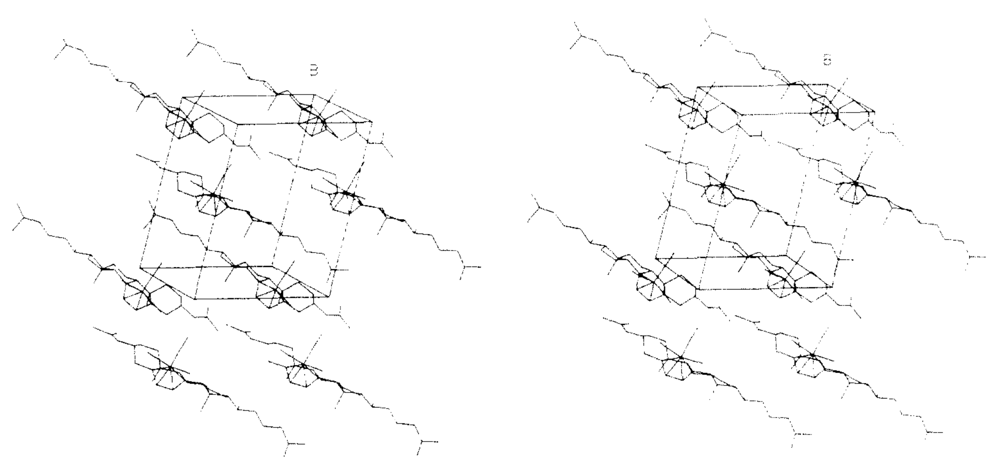


Fig. 2. Stereo view of the unit cell of **11**.

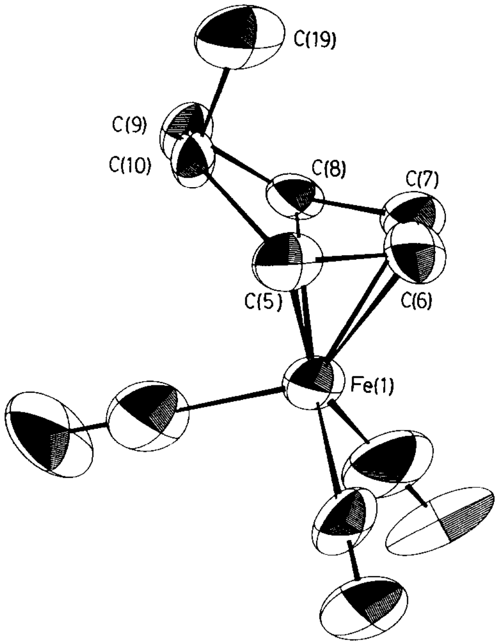


Fig. 3. View of the coordinated B ring of **11** showing the envelope conformation adopted by the cyclohexadiene moiety.

Experimental section

All reactions were carried out under an atmosphere of dry nitrogen employing conventional benchtop and glovebag techniques. All solvents were dried according to standard procedures before use [38]. ^1H and ^{13}C NMR spectra were recorded at 500 MHz and 125.7 MHz, respectively, by using a Bruker AM 500 spectrometer equipped with a 5 mm dual frequency $^1H/^{13}C$ probe. All spectra were recorded at 30°C and are referenced to TMS. Proton spectra were acquired in 16 scans over a 3000 Hz spectral width in 32K data points, processed using Gaussian multiplication

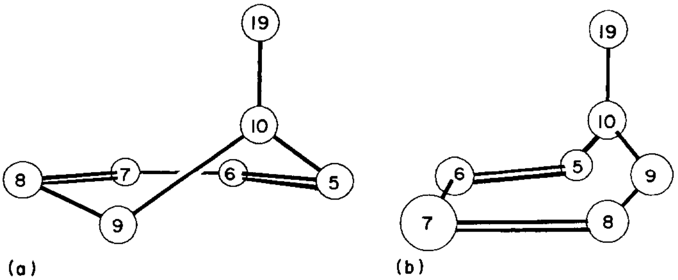


Fig. 4. (a) Half-chair conformation of a cyclohexadiene ring showing the pseudo C_2 axis passing through the mid-points of the C(6)–C(7) and C(9)–C(10) bonds; (b) envelope conformation of a cyclohexadiene ring showing the pseudo mirror plane which bisects the C(6)–C(7) and C(9)–C(10) bonds.

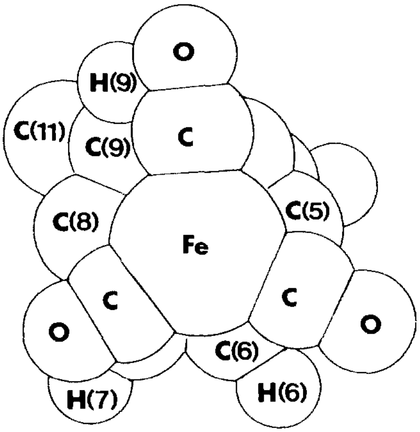
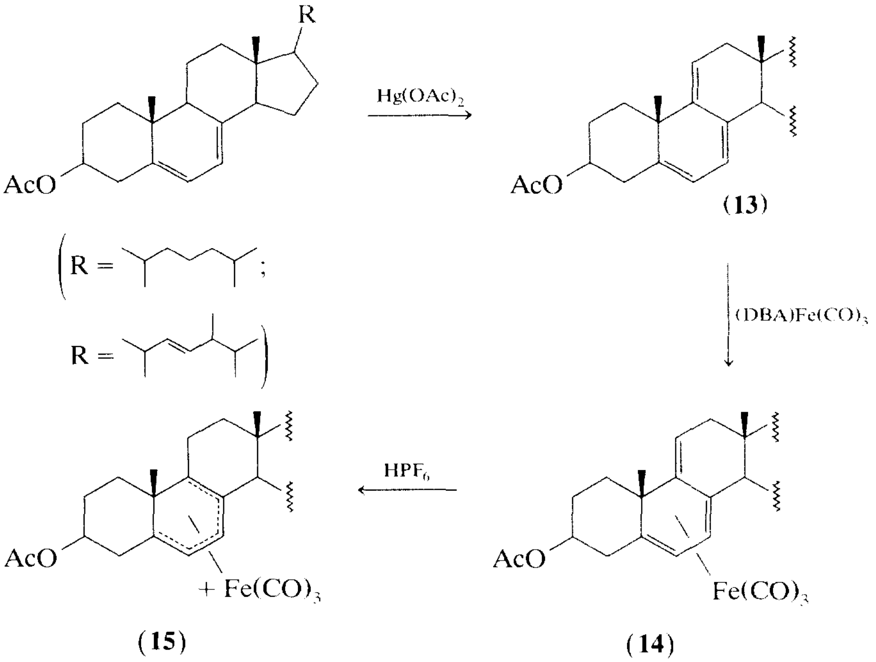


Fig. 5. Space-filling model of the α-face of the B ring of **11** showing how the Fe(CO)$_3$ tripod blocks access to the 9α-hydrogen atom.

for line enhancement and zero filled to 64K before transformation. Homonuclear and heteronuclear chemical shift correlated spectra were obtained by using standard techniques [39,40].

7-Dehydrocholesterol and ergosterol were converted to their acetates according to the procedure of Stansbury [41]; the corresponding Fe(CO)$_3$ complexes, **11** and **12**, respectively, were prepared by reaction of the diene with (benzylideneacetone)Fe(CO)$_3$ [16]. 9,11-Dehydroergosteryl acetate (**13**) was prepared from



Scheme 2. Route to B-ring cationic complexes.

Table 6

^{1}H NMR chemical shifts for 9,11-dehydroergosteryl acetate (**13**) [a], Fe(CO)$_3$ complex (**14**) [a] and cation (**15**) [b]

Proton	**13**	**14**	**15**
1α	1.55	1.21	2.35
1β	1.78	1.65	2.12
2α	1.90	2.00	2.05
2β	1.75	1.50	1.50
3α	4.90	5.10	4.90
4α	2.50	2.10	2.25
4β	2.50	1.90	1.88
6	5.70	5.12	5.53
7	5.50	4.50	6.85
11	5.42	5.00	1.98/1.68
12α	2.25	1.85	1.85
12β	2.38	2.00	2.38
14α	2.25	2.15	1.95
15α	1.55	1.58	1.82
15β	1.55	1.20	1.35
16α	1.85	1.85	1.75
16β	1.35	1.60	1.45
17α	1.25	1.00	1.20
18Me	0.65	0.50	0.58
19Me	1.21	0.95	0.82
20	2.05	1.94	1.95
21Me	1.05	0.99	0.90
22	5.18	5.00	5.10
23	5.30	5.08	5.21
24	1.95	1.90	1.85
25	1.50	1.50	1.30
26Me	0.92	0.80	0.75
27Me	0.92	0.90	0.75
28Me	1.00	1.00	0.85
30Me	1.78	2.00	1.95

[a] In C_6D_6. [b] In CD_3CN.

12 by use of mercuric acetate/acetic acid, according to the procedure of Djerassi [42].

*Preparation of (5-8-η-9,11-dehydroergosteryl acetate)Fe(CO)$_3$ (**14**)*

By analogy to the method of Johnson [16], 9,11-dehydroergosteryl acetate (**13**) (0.35 g, 0.8 mmol) was dissolved in toluene (25 mL) and (benzylideneacetone)Fe(CO)$_3$ (0.27 g, 0.93 mmol) was added. The mixture was heated under reflux for 6 h, cooled to room temperature, filtered through Celite and the solvent removed *in vacuo*. The residue was chromatographed on silica gel by using hexane/toluene (1 : 1) as eluent. The purified fraction was triturated with cold methanol to remove any residual unreacted steroid and the Fe(CO)$_3$ complex was isolated as an orange oil which exhibited ν(CO) (in cyclohexane) at 1975 and 1965 cm^{-1}. When a dichloromethane solution of **14** was stirred at room temperature for 3 h with trityl tetrafluoroborate, the starting materials were recovered and no evidence for the formation of **15** was obtained.

Table 7

^{13}C NMR chemical shifts for 9,11-dehydroergosteryl acetate (**13**), $Fe(CO)_3$ complex (**14**) and cation (**15**)

Carbon	**13**	**14**	**15**
1	23.19	22.30	35.42
2	28.73	28.64	27.43
3	74.09	73.23	70.90
4	37.93	37.97	25.76
5	140.39	81.66	87.19
6	119.63	81.99	96.00
7	116.55	79.54	85.10
8	144.75	84.20	109.42
9	145.10	147.30	117.00
10	Not observed	38.86	38.19
11	122.25	115.52	23.44
12	43.27	41.37	35.80
13	42.35	43.35	42.90
14	51.43	53.25	51.63
15	38.40	36.12	35.14
16	29.38	28.02	29.54
17	56.34	55.25	54.88
18Me	11.83	11.46	11.80
19Me	30.24	30.16	32.09
20	40.86	40.69	40.79
21Me	20.92	20.85	21.04
22	136.07	135.81	135.50
23	132.33	132.40	132.30
24	43.27	43.23	43.64
25	33.44	33.44	33.83
26Me	19.88	19.89	19.90
27Me	20.20	20.19	20.23
28Me	17.92	17.88	17.90
29(CO)	169.42	169.10	170.00
30Me	20.92	20.85	21.59
$Fe(CO)_3$	–	213.47	204.10

Synthesis of [5-9-η-(7-dehydrocholestadienylium acetate)tricarbonyliron]hexafluorophosphate (15)

(9,11-Dehydroergosteryl acetate)$Fe(CO)_3$ (**14**) (0.7 g, 1.2 mmol) in ether (25 mL) was treated dropwise with 300 μL of 70% HPF_6. The resulting solution was cooled to −78°C in a dry ice/acetone bath and, after 20 min, a yellow precipitate of **15** (0.21 g, 0.29 mmol; 24%) was obtained, m.p. 140°C ν(CO), (in acetonitrile) at 2120, 2078 and 2040 cm^{-1}. Anal. Found: C, 54.84; H, 6.10. $C_{33}H_{45}O_5FePF_6$ calc.: C, 55.00; H, 6.25%.

Reactions of 15 with nucleophiles

An acetonitrile solution of **15** was stirred at room temperature with excess ammonium thiocyanate and, over a period of 20 min, the yellow colour became less intense. Removal of the solvent and extraction with ether led to recovery of the triene **14**, identified by comparison of its ^1H NMR spectrum with that of an authentic sample. Likewise, sodium methoxide in methanol gave the triene **14** in almost quantitative yield.

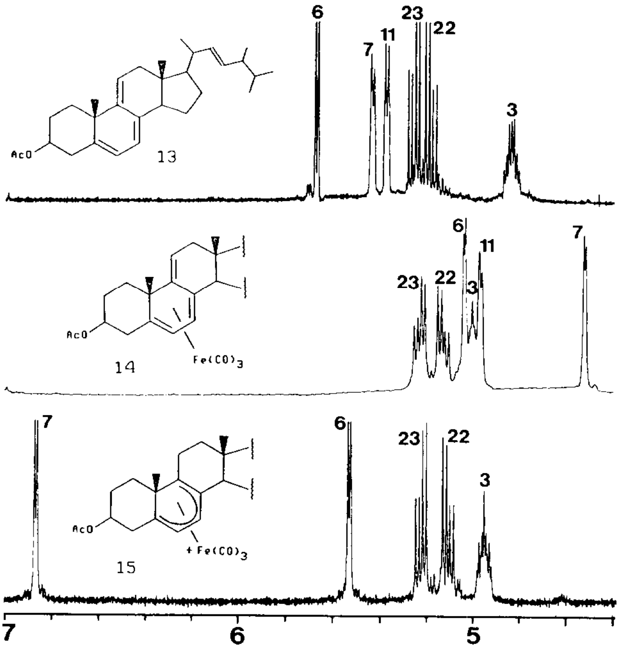
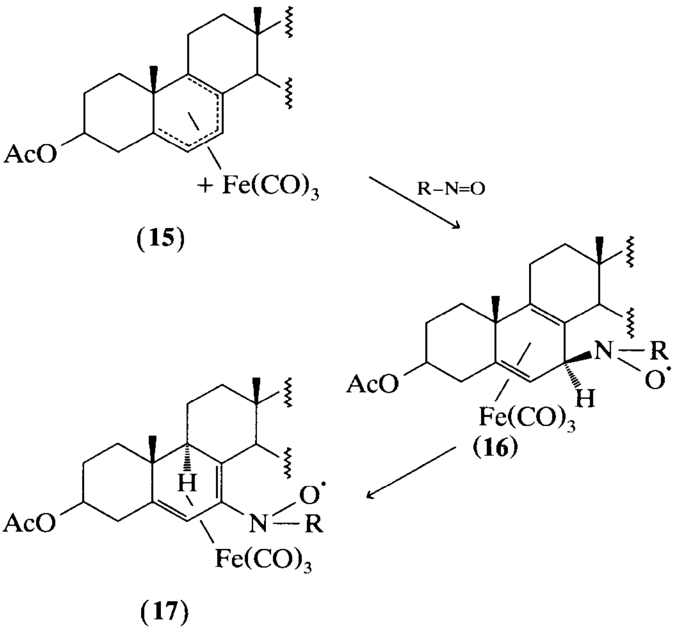


Fig. 6. Sections of the 500 MHz ^1H NMR spectra of **13**, **14** and **15**; the former two spectra were recorded in C_6D_6 and the salt **15** was dissolved in CD_3CN.



Scheme 3. Reaction of **13** with nitrosopentamethylbenzene.

*X-Ray crystal structure of (7-dehydroergosteryl acetate)tricarbonyliron(0) (**13**)*

Yellow plate-like crystals of **13** were grown from hexane/dichloromethane and examined under a polarizing microscope for homogeneity. A well formed single crystal, 0.52 × 0.39 × 0.26 mm^3, suitable for X-ray diffraction was selected and sealed in a Lindemann capillary. The density was determined by flotation in an aqueous solution of $ZnBr_2$. Unit cell parameters were determined from a least-squares fit of ω, ϕ and 2θ for 15 reflections in the range $19.7° < 2\theta < 27.2°$ recorded on a Nicolet P3 diffractometer with use of graphite-monochromated Mo-K_α radiation (λ = 0.71069 Å) at 22°C. Details of the data collection procedure are listed in Table 1. Intensity data were also recorded on a Nicolet P3 diffractometer with a coupled θ(crystal)–2θ(counter) scan for 4483 reflections (h, $\pm k$, $\pm l$ with $2\theta \leq 45°$. Data were corrected for Lorentz polarization effects but not for absorption (estimated error in F = 2.94%). Two standard reflections (0, −7, 3; 1.34%) and 5, 0, −2; 0.51%) were monitored every 48 reflections and showed no sign of crystal decomposition or instrument instability.

The coordinates of the iron atoms were found from a three-dimensional Patterson synthesis with use of the program SHELXS-86 [43]. Full-matrix least-squares refinement of the coordinates of Fe(1) — the coordinates of Fe(2) were held fixed to define the origin — followed by a three-dimensional electron density synthesis revealed most of the non-hydrogen atoms. The refinement of the carbon and oxygen atoms was hindered by the fact that the two independent molecules were strongly correlated and it was necessary in the early stages of the refinement to constrain certain bond distances to their theoretical values. A damping factor during refinement was applied and the bond length restraints slowly removed. After refinement, the temperature factors of the non-hydrogen atoms were made anisotropic and further full-matrix least-squares refinement, which minimized $(\Sigma w(|F_o| - |F_c|)^2$, was terminated when the maximum shift/error reached 0.141 (molecule 1), 0.233 (molecule 2). Correction for secondary extinction was made by the method in SHELX-76 [44]. Final $R_1 = 0.0572$, $R_2 = 0.0668$ for 3135 reflections with $I > 3\theta(I)$. Alternate refinement where coordinates x, y, z were replaced by $-x$, $-y$, $-z$ gave $R_1 = 0.0594$, $R_2 = 0.0694$ for 3135 reflections; this confirms the assignment for the correct hand for the structure. (Although a full data set of $\pm h$, $\pm k$, $\pm l$ was not taken, the correct hand is implicit from that of the starting material, the absolute configuration of which is known.) Scattering curves from ref. 45 were applied during refinement of the structure, and anomalous dispersion corrections for Fe were applied from ref. 46. All calculations were performed on a VAX 8650 computer. Programs XTAL [47] for data reduction, SHELXS-86 [43] for structure solution, SHELX-76 [44] for structure refinement, MOLGEOM [48] for molecular geometry, and SNOOPI [49] for drawing programs were used. Atomic positional parameters, temperature factors, and selected bond lengths and angles appear in Tables 2–5.

Acknowledgements

Acknowledgement is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research. Financial support from the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged. Finally, we thank Professor J.D.

Dunitz (ETH, Zurich) for his valuable advice concerning the solution of the X-ray structure.

References

1 R.E. Perrier and M.J. McGlinchey, Can. J. Chem., 66 (1988) 3003, and refs. therein.

2 H. El-Amouri, M. Gruselle, P.A. Jackson, G. Jaouen and J. Vaissermann, Organometallics, 9 (1990) 2871.

3 K.M. Nicholas and J. Siegel, J. Am. Chem. Soc., 107 (1985) 4999.

4 G. Jaouen, A. Vessières, S. Top, A.A. Ismail and I.S. Butler, J. Am. Chem. Soc., 107 (1985) 4778.

5 G. Jaouen and A. Vessières, Pure Appl. Chem., 61 (1989) 565.

6 G. Jaouen, A. Vessières, S. Top, M. Savignac, A.A. Ismail and I.S. Butler, Organometallics, 6 (1987) 1985.

7 A. Vessières, G. Jaouen, M. Gruselle, J.L. Rossignol, M. Savignac, S. Top and S. Greenfield, J. Steroid Biochem., 30 (1988) 301.

8 S. Top, G. Jaouen, A. Vessières, J.P. Abjean, D. Davoust, C.A. Rodger, B.G. Sayer and M.J. McGlinchey, Organometallics, 4 (1985) 2143.

9 B. Mailvaganam, R.E. Perrier, B.G. Sayer, B.E. McCarry, R.A. Bell and M.J. McGlinchey, J. Organomet. Chem., 354 (1988) 325.

10 R.M. Moriarty, Y-Y. Ku, U.S. Gill, R. Gilardi, R.E. Perrier and M.J. McGlinchey, Organometallics, 8 (1989) 960.

11 A. Vessières, S. Tondu, G. Jaouen, S. Top, A.A. Ismail, G. Teutsch and M. Moguilewsky, Inorg. Chem., 27 (1988) 1852.

12 A. Vessières, S. Top, A.A. Ismail, I.S. Butler and G. Jaouen, Biochemistry, 27 (1988) 6659.

13 M. Savignac, G. Jaouen, C.A. Rodger, R.E. Perrier, B.G. Sayer and M.J. McGlinchey, J. Org. Chem., 51 (1986) 2328.

14 S. Top, M. Gunn, G. Jaouen, J. Vaissermann, J.-C. Daran, J.R. Thornback and M.J. McGlinchey, Organometallics, 11 (1992) 1201.

15 D.H.R. Barton, A.A.L. Gunatilaka, T. Nakanishi, H. Patin, D.A. Widdowson and B.R. Worth, J. Chem. Soc, Perkin Trans. 1, (1976) 821.

16 G. Evans, B.F.G. Johnson and J. Lewis, J. Organomet. Chem., 102 (1975) 507.

17 B.M. Trost and T. Verhoeven, J. Am. Chem. Soc., 100 (1978) 3435.

18 D.J. Collins, W.R. Jackson and R.N. Timms, Aust. J. Chem., 30 (1977) 2167.

19 S. Top, A Vessières, J.B. Abjean and G. Jaouen, J. Chem. Soc., Chem. Commun., (1984) 428.

20 G. Jaouen, S. Top, A. Laconi, D. Couturier and J. Brocard, J. Am. Chem. Soc., 106 (1984) 2207.

21 J. Andrieux, D.H.R. Barton and H. Patin, J. Chem. Soc, Perkin Trans. 1, (1977) 359.

22 D.H.R. Barton, S.G. Davies and W.B. Motherwell, Synthesis, (1979) 265.

23 A.J. Birch and L.F. Kelly, J. Organomet. Chem., 285 (1985) 267, and refs. therein.

24 A.J. Pearson, Science, 223 (1984) 895.

25 A.J. Pearson, Acc. Chem. Res., 13 (1980) 463.

26 H. Alper and C.C. Huang, J. Organomet. Chem., 50 (1973) 213.

27 A.J. Birch and W.D. Raverty, unpublished data quoted in ref. 25.

28 W.L. Duax, C.M. Weeks and D.C. Rohrer, in N.L. Allinger and E.L. Eliel (Eds.), Top. Stereochem., 9 (1976) 271.

29 P.B. Braun, J. Hornstra, C. Knobler, E.W.M. Rutten and C. Romers, Acta Crystallogr., 29 (1973) 463.

30 W.L. Duax, D.C. Rohrer, R.H. Blessing, P.D. Strong and A. Segaloff, Acta Crystallogr., 35 (1979) 2656.

31 M.R. Churchill and R. Mason, Proc. R. Soc., London, Ser. A, 301 (1967) 433.

32 F.A. Cotton and J.M. Troup, J. Organomet. Chem., 77 (1974) 369.

33 P. Dodman and T.A. Hamor, J. Chem. Soc., Dalton Trans., (1974) 1010.

34 J. Drew, J.B. Brisson, P. Morand and A.G. Szabo, Can. J. Chem., 65 (1987) 1784.

35 A.J. Birch, P.W. Westerman and A.J. Pearson, Aust. J. Chem., 29 (1976) 1671.

36 B.F.G. Johnson, J. Lewis, D.G. Parker and G.R. Stephenson, J. Organomet. Chem., 194 (1980) C14.

37 L. Li, R.E. Perrier, D.R. Eaton and M.J. McGlinchey, Can. J. Chem., 67 (1989) 1868.

38 D.D. Perrin, W.L.F. Armarego and D.R. Perrin, Purification of Laboratory Chemicals, Pergamon Press, New York, 1980.

39 A.E. Derome, Modern Techniques for Chemistry Research, Pergamon Press, Oxford, 1986.

40 J.K.M. Sanders and B.K. Hunter, Modern NMR Spectroscopy — A Guide for Chemists, Oxford University Press, Oxford, 1987.

41 H.A. Stansbury, J. Am. Chem. Soc., 65 (1943) 1243.

42 C. Delseth, Y. Kashman and C. Djerassi, Helv. Chim. Acta, 62 (1979) 2037.

43 G.M. Sheldrick, SHELXS-86, Program for Crystal Structure Solution, University of Göttingen, Germany, 1986.

44 G.M. Sheldrick, SHELX-76, Program for Crystal Structure Determination, University of Cambridge, UK, 1976.

45 D.T. Cromer and J.B. Mann, Acta Crystallogr., Sect. A, 24 (1968) 231.

46 D.T. Cromer and D. Liberman, J. Chem. Phys. 53 (1970) 1891.

47 J.M. Stewart and S.R. Hall, The XTAL system of crystallographic programs, Technical report TR-1364, University of Maryland, College Park, USA, 1983.

48 J. Stephens, MOLGEOM adapted from CUDLS, McMaster University, Canada, 1973.

49 K. Davies, CHEMGRAF suite: SNOOPI, Chemical Design Ltd., Oxford, UK, 1983.