

Estrone Sulfate: Production Rate and Metabolism in Man

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Research Article

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The conversion of plasma E_1S to plasma estrone and estradiol was studied. The calculated transfer factors were: $\rho^{E_1SE_1} = 0.21$, $\rho^{E_1SE_2} = 0.014$. Essentially, similar data were obtained when E_1S was given by mouth to two subjects.

We conclude: (a) E_1S is a major circulating plasma estrogen and has a long plasma half-life; (b) the large contributions of estrone and estradiol to plasma E_1S are more than sufficient to account for all the circulating plasma E_1S .

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ABSTRACT Since estrone sulfate (E_1S) is present at high concentration in plasma, we have examined the parameters of the plasma estrone, estradiol, E_1S system. The metabolic clearance rate of E_1S was 157 liter/day (range 70–292) in men and women. Estimated plasma production rates of E_1S were (μ grams per day): men, 77; women, early follicular phase, 95; women, early luteal phase, 182. The conversion of plasma estrone and estradiol to E_1S was measured and from these data and the metabolic clearance rates of the estrogens, the transfer factors were $\rho^{E_1S/E_1} = 0.54$ and $\rho^{E_1S/E_2} = 0.65$. Using average production rates, all plasma E_1S could be shown to be derived from plasma estrone and estradiol.

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INTRODUCTION

Estrone-3-sulfate (E_1S)¹ is the major component of the conjugated equine estrogens and of other estrogenic preparations and has been used for over 30 years for treatment of the postmenopausal woman. Although estrone sulfate has been identified in human urine, little is known of its blood levels and metabolism. Twombly and Levitz showed that estrone sulfate had a long half-

life in blood (1), and Purdy, Engel, and Oncley (2) found that it was the major plasma metabolite of estradiol and that it was present in high concentration in pregnancy. During previous studies of estrogen metabolism we had postulated (3) that there was another plasma estrogen compartment in equilibrium with plasma estrone (E_1) and estradiol (E_2). Since it seemed probable that this compartment was estrone sulfate, we initiated studies of the origin, rates of metabolism, blood levels, and conversions of estrone sulfate. These studies have confirmed the finding that E_1S is an important plasma metabolite of estradiol and have defined the production rate of E_1S and its interconversions with estrone and estradiol.

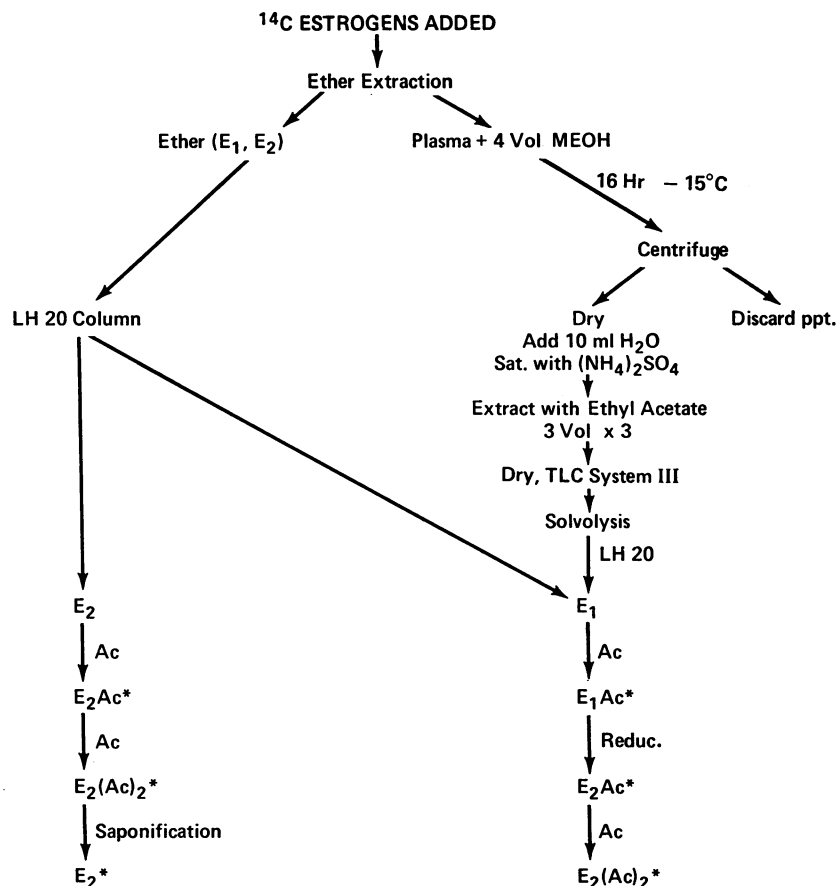
METHODS

Materials. Estrone-6,7-³H, estradiol-17 β -6,7-³H, estrone-3-NH₄-sulfate-6,7-³S (40 Ci/mmol), and estrone-4-¹⁴C and estradiol-17 β -4-¹⁴C (45 mCi/mmol) were purchased from New England Nuclear Corp., Boston, Mass. Portions of ³H- and ¹⁴C-labeled steroids were combined and radiochemical purity demonstrated before use by constancy of ³H : ¹⁴C ratio through a series of derivatives as shown in Fig. 1. Estrone-3-NH₄-sulfate-4-¹⁴C (45 mCi/mmol) was prepared from estrone-4-¹⁴C (45 mCi/mmol) by a modification of the method of Mumma, Hoiberg, and Weber (4). Estrone-4-¹⁴C was dried in a 1 ml centrifuge tube and redissolved in 20 μ l of dimethyl formamide (DMF) and chilled to 0°C in an ice-water bath. To the estrone in DMF, 10 μ l of chilled 14% concentrated sulfuric acid in DMF (v/v) was added and mixed quickly with a vortex mixer. This was followed by addition of 25 μ l of 3 M dicyclohexylcarbodiimide (DCC) in DMF prepared by adding 0.150 g DCC to 0.0240 ml DMF. After mixing, the solution turned a thick white, and was then incubated at 0°C for an additional 15 min. 1 ml of 1 M NH₄OH in methanol was added, the solution mixed, and centrifuged. The supernatant was chromatographed by thin-layer chromatography (TLC) (5) to separate mono-sulfate from free steroids.

Radiochemical purity of estrone-3-sulfate-4-¹⁴C was demonstrated by mixing it with portions of estrone-3-NH₄-sulfate-6,7-³H and demonstrating constancy of ³H : ¹⁴C ratios through TLC, isolation, solvolysis of E_1S , and recrystallization of estrone to constant specific activity. Before any study involving the use of estrone sulfate-³H, the steroid was dissolved in sterile saline and preextracted with ether to re-

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¹ *Abbreviations used in this paper:* DCC, dicyclohexylcarbodiimide; DHS, dehydroepiandrosterone sulfate; DMF, dimethyl formamide; E_1 , estrone; E_2 , estradiol; E_1S , estrone-3-sulfate; MCR, metabolic clearance rate; RBC, red blood cells; TLC, thin-layer chromatography.



*Fraction counted for $^3\text{H}/^{14}\text{C}$

FIGURE 1 Flow chart for measurement of tritium in plasma estrone, estradiol, and E_1S during infusion of ^3H estrogens.

move any contaminating free estrogen. The ether phase was discarded, excess ether removed by an air stream, and portions taken in triplicate for determination of E_1S - ^3H . An appropriate volume of sterile saline was then drawn up in a glass syringe for injection or addition to an infusion bottle.

Chromatoquality estrone and estradiol (Calbiochem, Los Angeles, Calif.) were used without further recrystallization. Solvents were spectroquality and used without further purification. TLC was performed on Merck precoated silica gel GF-254 20×20 cm glass plates (Merck Chemical Division, Merck & Co., Inc., Rahway, N. J.). The systems used for separations of various steroid and the R_f values are previously described (3, 5, 6). Column chromatography was performed on small Sephadex LH-20 columns (Pharmacia Fine Chemicals Inc., Piscataway, N. J.) which separate E_1 and E_2 as described previously (5).

Subjects. Normal subjects, (Nos. 2-18), ages 18-30 yr were hospitalized at the National Institutes of Health and received no medications. Each woman had normal cyclic menses. Subject 16 was a 28 year old euthyroid subject with a benign thyroid nodule. Subject 1 was a normal man, age 48, in good health.

Clearance rates. Determinations of metabolic clearance rate (MCR) were started at 7:30 a.m. with subjects re-

maining in the basal state until the end of the study. The infusion techniques were performed as described previously (7).

All short infusions were begun with a $10 \mu\text{Ci}$ bolus given i.v. over 1 min, 30 min later an infusion of approximately $10 \mu\text{Ci/hr}$ was begun and maintained at a constant rate until the end of the study. The duration of the short infusions was usually 165 min from the time of the bolus and varied from 135 min in earlier studies to 210 min in later studies, 30-40 ml of blood was drawn at various times after the bolus was given; the heparinized plasma was separated by centrifugation and stored at -16°C until extracted.

To measure the MCR of E_1S , 20-40 μCi of E_1S - ^3H was injected over 1 min at 9:00 a.m. via an antecubital vein. 10-ml blood samples were taken at $\frac{1}{2}$, 1, 2, 4, 6, and 8 hr and 20-35-ml blood samples were taken at 11, 14, 19, and 24 hr. Blood was heparinized, centrifuged immediately, and the plasma frozen at -15°C until extracted. Subjects were kept at bed rest with bathroom privileges and fed light meals as desired for the duration of the study except for subjects 1 and 2, who were allowed normal daily activities.

Calculations. The symbols and calculations for the several parameters of the system are essentially those used by Horton and Tait (8). Since all measurements were made in

TABLE I
Metabolic Clearance Rates—Estrone-3-Sulfate-6, 7-³H—Bolus Injections

Subject	Sex and age	Estrone-3-sulfate- ³ H <i>cpm</i> × 10 ⁻¹	Plasma levels of estrone-3-sulfate-6, 7- ³ H					Y intercept <i>cpm/liter</i> × 10 ⁻⁴	Volume of distribution <i>liter</i>	γ (slope) <i>hr</i> ⁻¹	MCR <i>liter/day</i>	MCR _{BS} <i>liter/day/m</i>
			0.5-1.0 hr	2.0-5.0 hr	6.0-11 hr	14-24 hr						
1	M 48	1.12	26.2 (0.5)* 20.4 (1)	16.7 (2) 17.8 (3) 17.0 (4)	14.5 (6) 8.49 (9)	3.69 (14) 0.68 (24)	28.1	39.9	0.149	143	76.3	
2	M 29	1.12	17.3 (0.5) 15.4 (1)	13.1 (2) 13.6 (3) 11.8 (4)	8.55 (6) 8.87 (9)	3.16 (14) 0.35 (24)	21.6	51.9	0.158	197	95.7	
3	M 30	1.55	19.3 (0.5) 14.6 (1)	11.5 (2) 8.2 (4)	10.3 (6) 3.0 (11)	2.32 (14) 1.53 (19) 0.78 (24)	16.7	93.4	0.131	292	163	
4	M-21	1.54	27.3 (1)	28.3 (2.25) 19.3 (4.25)	23.4 (6) 15.8 (8) 11.3 (11)	13.4 (14) 7.72 (19) 4.46 (24)	30.9	49.8	0.0762	91.1	46.8	
5	M 21	1.54		20.4 (2.25) 13.2 (4.25)	17.2 (6) 11.9 (8) 11.7 (11)	10.4 (14) 4.95 (19) 4.53 (24)	22.3	69.1	0.0679	113	55.4	
Mean ±SEM (No. 1-5) 6	Male	—	—	—	—	—	—	60.8 ±9.4	0.116 ±0.019	167 ±36	87.4 ±21	
7	F 18	2.07	39.7 (1)	33.9 (2) 18.5 (4)	16.0 (6) 9.6 (8)		47.8	43.3	0.199	207	141	
	F 18	1.43	45.6 (1)	47.7 (2) 34.8 (4)	26.7 (6) 20.9 (8) 16.7 (11)	12.7 (14) 8.09 (19) 6.34 (24)	48.8	29.3	0.0913	64.2	39.4	
8	F 18	1.43	72.9 (1)	61.9 (2) 31.0 (4)	25.7 (6) 22.3 (8) 14.1 (11)	10.4 (14) 4.05 (19) 2.21 (24)	72.2	19.8	0.147	69.9	44.5	
9	F 22	1.47	35.6 (0.33) 26.0 (0.75) 22.3 (1.5)	18.6 (3) 12.6 (5)	8.14 (7.5) 5.19 (11)	3.49 (14.5) 1.99 (20) 1.44 (24)	27.1	54.2	0.132	172	116	
10	F 21	1.47	32.6 (1.5)	22.0 (3) 8.2 (5)	5.96 (7.5) 2.99 (11)	1.39 (14.5) 0.29 (20) 0.29 (24)	34.5	42.6	0.219	224	134	
Mean ±SEM (No. 6-10)	Female	—	—	—	—	—	—	37.8 ±6.0	0.158 ±0.023	146 ±34	94.1 ±22	

* Numbers in parentheses are times of collection.

plasma, the compartment is not indicated and the superscript indicates the steroids. Production rate equals $MCR \times$ plasma concentration. The conversion ratio, $C^{E_1S}_{E_1}$, is the ratio of radioactivity of product E_1S , to precursor, E_1 , when equilibrium has been reached. The transfer factor, $\rho^{E_1S}_{E_1} = C^{E_1S}_{E_1} \times MCR_{E_1S}/MCR_{E_1}$, is the fraction of plasma E_1 production rate converted to plasma E_1S .

Isolation of labeled estrogens. All plasma samples were processed within 3 wk of collection and were treated identically, as shown in Fig. 1. To monitor recovery appropriate amounts (100–1000 cpm) of ^{14}C estrogens were added to each plasma sample. All samples from a single study were processed together. After alkalinizing with 4 drops of NH_4OH , the plasma was extracted three times with 2 vol of ether. The ether extracts containing the neutral steroids were under air and stored until further processing in 5 ml of absolute ethanol at $-15^\circ C$. Previous tests had shown that only 1–2% of estrone sulfate is removed by the ether, probably in the small amount of water soluble in the ether. Estrone sulfate proved stable in the cold so that any contaminating E_1S was separated from free estrogens by the subsequent column chromatography. The ether-extracted plasma containing the conjugated steroids, including E_1S , was warmed to $40^\circ C$ and the residual ether removed under an air stream. Recovery of estrone sulfate was found to be inversely related to the quantity of ether remaining at this point. To the plasma was then added 4 vol of absolute methanol to precipitate proteins. Each sample was mixed by shaking for 30 sec and stored at $-15^\circ C$ for at least 16 hr to precipitate lipids. Centrifugation and decanting of the supernatant yielded a yellow methanol solution which contained about 80% of the starting E_1S . After addition of 4 more drops of NH_4OH , samples could be stored indefinitely in the cold until further processing.

Processing E_1S . After 16 hr at $-15^\circ C$, the methanol-precipitated plasma was centrifuged in 100-ml centrifuge

tubes at 2000 *g* for 20 min. The yellow supernatant was decanted and either stored as described above or processed. The supernatant was dried under vacuum until only 2–5 ml of cloudy yellow water remained. This was quantitatively transferred to a 40 ml glass-stoppered tube (final vol. = 10 ml H_2O), alkalinized with 5 drops of concentrated NH_4OH , saturated with dry $(NH_4)_2SO_4$, and extracted three times with 2 vol of ethyl acetate. The ethyl acetate quantitatively removed the E_1S . Recovery to this point is 60–70%. The ethyl acetate was combined and reduced in volume, and the residue was spotted onto TLC plates and the monosulfate fraction isolated (5). Dehydroepiandrosterone sulfate (DHS) was used as a marker on both sides of the plate and the DHS identified by streaking with Allen's reagent. After elution from the TLC plate, the samples were dried and then resuspended in 0.2 ml of absolute ethanol. Solvolysis was performed by addition of 5 ml of 10% glacial acetic acid in ethyl acetate and incubation in a tightly capped tube for 16 hr at $50^\circ C$. The solvents were removed under N_2 at $40^\circ C$. No washing was necessary, and previous tests demonstrated that the estrone was not altered by this procedure. From this point on, derivative formation and portioning for determination of $^3H:^{14}C$ ratios is as previously described for estrone (6). Recovery of $E_1S-^{14}C$ to the isolation of estrone averaged 50%. In sample studies this procedure was shown to separate completely E_1 and E_1S in plasma since addition of a 100-fold excess of E_1-^3H did not influence the values obtained for tritiated E_1S ; and conversely, addition of 100-fold excess of E_1S-^3H did not influence the values obtained for tritiated E_1 .

Processing E_1 and E_2 . Sample tubes containing neutral steroids in ethanol were dried under N_2 at $40^\circ C$ and estrone and estradiol separated by column chromatography on Sephadex LH-20 (5). To the appropriate fraction was added 200 μg estrone or estradiol, and derivative formation carried out as shown on Fig. 1 and as previously described

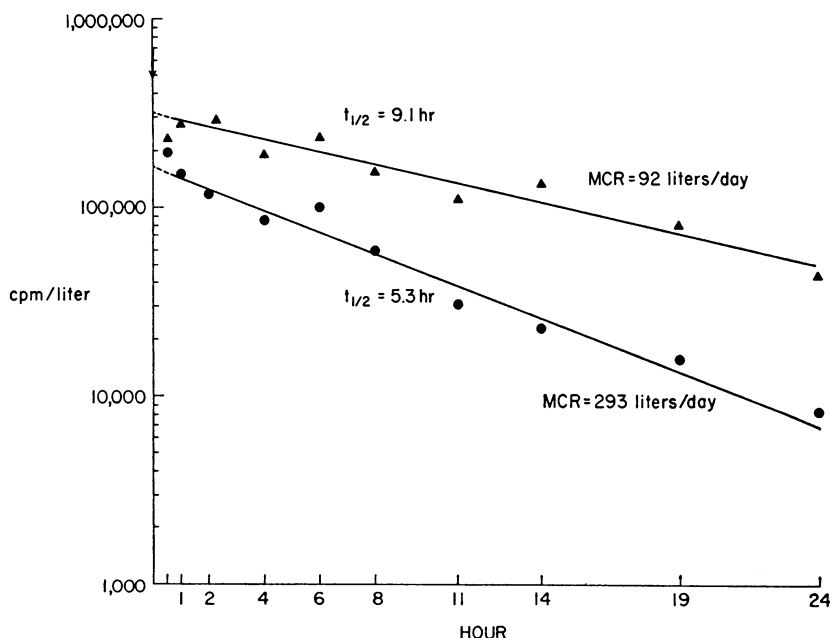


FIGURE 2 Representative data from a low and high MCR_{E_1S} . Infusion started at time 0. The points are the data points; the lines were determined by a computer program.

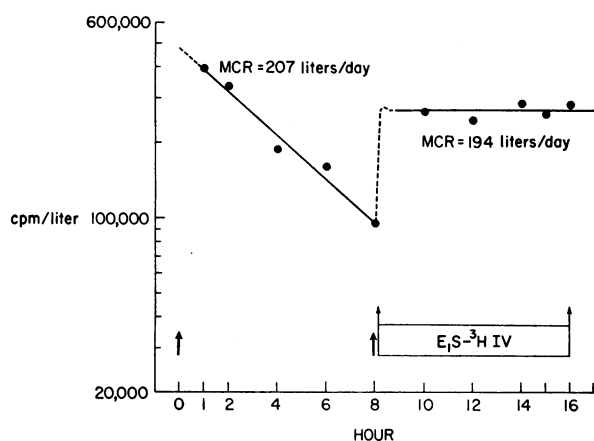


FIGURE 3 MCR_{E_2S} measured after injection of E_2S-^3H at time 0 and at 8 hr followed then by a continuous infusion of E_2S-^3H (subject 6).

(3, 6). After the first four studies were completed, it was evident that in no case did $^3H:^{14}C$ ratios change significantly after the first derivative was isolated, and that in all cases the $^3H:^{14}C$ ratio of the first derivative was the same as that of the final derivative. Hence, thereafter, only two derivatives were counted; the second was the same as the first in the remainder of the studies. In no instance was fewer than 15 cpm above background of ^{14}C present in the second derivative, and except in the case of the E_2 levels during E_2S infusions where conversion to E_2 was quite low, the $^3H:^{14}C$ ratio was greater than 1.0 and less than 8.0 in all samples.

Estrone sulfate binding to red blood cells (RBC). Portions of packed RBC taken during E_2S-^3H infusions were examined for binding of E_2S . We found little (<5%) of the E_2S-^3H present in whole blood to be associated with RBC.

Counting methods. Radioactivity was measured as previously described (3, 6). All samples were counted to either a minimum of 3000 counts in the carbon channel or for 100 min. Samples were spot checked for differences in quenching and none were found.

Plasma estrogen concentrations. Methods for measurement of plasma concentration of E_1 , E_2 , and E_2S have been

described (5) and normal values for our laboratory are shown in Table III. These values include all patients used in the infusion studies and agree well with those obtained by others (9-11).

Plasma concentration of estradiol monosulfate. To determine if estradiol monosulfate was an important metabolite of estradiol or if it was present in plasma in significant amounts, the following studies were performed. (a) We attempted to isolate E_2S-^3H from plasma obtained from two subjects during E_2-^3H infusion. The entire monosulfate fraction was solvolyzed and the E_1 and E_2 fractions isolated. Radiochemical purity was demonstrated only for E_1-^3H , but tritium present in the E_2-^3H fraction was approximately 10% that present as E_1-^3H . Hence conversion of E_2 to E_2S could occur maximally at only $\frac{1}{10}$ the rate of E_2 conversion to E_2S . (b) 15 random plasma samples were examined for E_2 monosulfate. No recovery trace was available for E_2-^3H-3 -sulfate or E_2-^3H-17 -sulfate, but recovery was assumed to be similar to that for E_2S determined simultaneously. After solvolysis of the monosulfate fraction from TLC, both E_1 and E_2 were isolated on Sephadex LH-20. The E_2 fractions were assayed and found to be indistinguishable from blank values (25-50 pg). Assuming the same recovery for E_2 monosulfate as for E_2S , this would mean that E_2S was present at less than 100-150 pg/ml plasma whereas E_2S was measured at concentrations of 250-1000 pg/ml.

RESULTS

E_2S metabolic clearance rates. The data for the disappearance of E_2S-^3H from plasma are shown in Table I. When the data for each subject were analyzed, it was found that in all cases, disappearance curves could be fitted by a single straight line, consistent with a one-compartment system described by a single Y intercept (volume of distribution) and a single slope (fractional pool turnover rate). Two representative studies are shown in Fig. 2. The lines of best fit were calculated by computer program, and the points shown are the data points. Metabolic clearance rates were calculated, assuming a one-compartment model, by the formula $MCR = V\gamma$, where V = the volume of distribution and γ = fractional pool turnover rate per unit

TABLE II
Plasma Concentrations and Production Rates (PR) of Estrone, Estradiol, and Estrone-3-Sulfate

	E_2S MCR	E_2S	E_2S PR	E_1 MCR*	E_1	E_1 PR	E_2 MCR*	E_2	E_2 PR
	liter/day	pg/ml	μg/day	liter/day	pg/ml	μg/day	liter/day	pg/ml	μg/day
Men	167	460	77	2380 (1177)†	47	112	1700 (892)	34	58
Women									
Follicular phase	146	654	95	1750 (1070)	62	109	1055 (642)	110	116
Women									
Luteal phase	146	1,246	182	1750	86	151	1055	193	204

* Average MCR for this laboratory.

† Numbers in parentheses, average MCR for this laboratory, expressed as liter/day per m².

TABLE III
Estrone-3-Sulfate-6,7-³H Infusions

Subject	Sex and age	E ₁ S+H cpm/day × 10 ⁻³	Steroid	Plasma tritium levels cpm × 10 ⁻³							C		ρE ₁ SE ₁ *	ρE ₁ SE ₂ *
				1.75 hr	2.0 hr	2.25 hr	2.75 hr	4.0 hr	6.0 hr	7.0 hr	8.0 hr	E ₁ H/E ₁ S+H E ₂ H/E ₁ S+H		
11	M 21	1.440	E ₁ S	387	427	441	519							
			E ₁		3.30	3.64	4.523							
			E ₁ /E ₁ S		0.0074	0.0083	0.0087					0.0081	0.127	
			E ₂		0.422	0.467	0.521							
12	F 19	1.203	E ₂ /E ₁ S		0.00099	0.0011	0.0010					0.0010		0.10
			E ₁ S	337	374	394	436							
			E ₁	3.97	4.65	4.67	5.40							
			E ₁ /E ₁ S		0.012	0.012	0.012					0.012	0.180	
13	F 20	0.9916	E ₂	0.661	0.725	0.636	0.596							
			E ₂ /E ₁ S	0.0020	0.0019	0.0016	0.0014					0.0017	0.012	
			E ₁ S	266	266	278	277							
			E ₁	5.61	5.75	5.90	5.98							
14	F 19	1.100	E ₁ /E ₁ S	0.021	0.022	0.021	0.022					0.021	0.30	
			E ₂	0.782	0.794	0.756	0.751							
			E ₂ /E ₁ S	0.0029	0.0030	0.0027	0.0027					0.0028		0.019
			E ₁ S		317	333	344	344	392	506				
6†	F 18	0.5250	E ₁		6.02	6.98	7.62	7.62	7.84	10.7				
			E ₁ /E ₁ S		0.0190	0.021	0.021	0.022	0.020	0.021		0.021	0.231	—
			E ₂		—	—	—	—	—	—		—	—	—
			E ₂ /E ₁ S		—	—	—	—	—	—		—	—	—
Mean	F 18	0.5250	E ₁ S		267	289	247	247	289	265	288			
			E ₁		5.93	5.71	5.71	5.71	7.59	7.08	7.25			
			E ₁ /E ₁ S		0.022	0.023	0.023	0.023	0.026	0.027	0.025	0.025	0.19	
			E ₂		0.966	0.935	0.935	0.935	0.972	1.01	0.985			
Mean			E ₂ /E ₁ S		0.0036	0.0038	0.0038	0.0038	0.0034	0.0038	0.0034	0.0036		0.014
													0.21	0.014

* Values for MCR_{E₁} or MCR_{E₂} performed in the same patient (Table V and VI) used for calculation of ρ. Otherwise average values from our laboratory used (Table III).

† Equilibrium was attained during infusion. MCR = 194 liter/day or 132 liter/day per m².

TABLE IV
Estrone-6,7-

Subject	Sex and age	Estrone- ³ H infusion	³ H-steroid	Plasma tritium levels		
				1.75 hr	2.0 hr	2.25 hr
		<i>cpm/day</i> × 10 ⁻³	<i>cpm</i> × 10 ⁻³ /liter			
【11】	M 21	1.048	E ₁	41.7	44.6	47.2
			E ₁ S	86.5	99.4	110
12	F 19	0.965	E ₁	45.4	43.5	43.5
			E ₁ S	89.3	101	117
13	F 20	0.992	E ₁	43.8	45.2	49.0
			E ₁ S	60.6	67.0	75.6
8	F 18	1.08	E ₁		(59.2)	
			E ₁ S		222	
Mean						

* Value for MCR_{E₁S} performed in the same patient (Table II) used for calculation of ρ ; otherwise average values for our laboratory used (Table III).

time. The average MCR_{E₁S} in five men was 167 liter/day or 87.4 liter/day per m². The average MCR of five women was 146 liter/day or 94.1 liter/day per m². The large differences among normal subjects are related both to differences in fractional turnover rate, γ (range 0.0679–0.219 pools/hr) and volume of distribution, V (range 20–93 liters). The range of volumes of distribution was roughly correlated with body surface area.

The validity of calculation of MCR_{E₁S} based on the assumption of a one-compartment system was tested by comparing in the same subject the MCR obtained in this way with that obtained by the constant infusion technique. In this study, we injected a bolus of E₁S into a normal subject, No. 6, and established a MCR_{E₁S} from the plasma disappearance curve over 8 hr. Subsequently, a calculated bolus of E₁S-³H was given followed by a continuous infusion of E₁S-³H for a further 8 hr achieving a constant plasma level of E₁S-³H (Fig. 3). From the data obtained after the injection of E₁S-³H (Table I), a MCR of 207 liter/day was calculated. The MCR calculated from the constant infusion data (Table III) was 194 liter/day. These two MCR are not different.

The production rate of E₁S was calculated from the MCR_{E₁S} and the measured plasma concentrations of E₁S (Table II). Average values for MCR and plasma E₁S concentrations in both men and women were used. In men, E₁S production averaged 77 μ g/day, not greatly different from E₁ and E₂ production rates. In women, E₁S production averaged 95 μ g/day during the early follicular phase; and 182 μ g/day during the luteal phase. Follicular and luteal phase E₁S production rates are compared with follicular and luteal E₁ and E₂ production rates (Table II). To convert E₁S production

rates to equivalent E₁ production rates, multiply E₁S values by 0.71.

Conversion ratios. C^{E₁SE₁} and C^{E₁SE₂} were measured in five subjects (Table III). Shown in Table III are the plasma levels of tritium in E₁, E₂, and E₁S; conversion ratios have been calculated at each time point. Though plasma levels of E₁S-³H, E₁-³H, and E₂-³H are increasing, the conversion ratios are constant and appear to represent equilibrium values. Each series of conversion ratios was examined for systematic trends or deviations from the mean. Only in subject 11 was there a suggestion that C^{E₁SE₁} was increasing during the period of observation. In subject 6, plasma levels of E₁-³H and E₁S-³H reached equilibrium as did the conversion ratios and the conversion ratio of 0.025, was the same as the average of the other subjects. The conversion ratio (C^{E₁SE₁}) averaged 0.017 in five studies. Transfer factors (ρ) were calculated using these conversion ratios and values for MCR_{E₁} and MCR_{E₁S} either measured in the same subject (Table IV) or using average values from our laboratory (Table III) (3). Transfer factor ($\rho^{E_1SE_1}$) averaged 0.21 (range 0.13–0.30) (Table III).

The conversion ratio (C^{E₁SE₂}) averaged 0.0023 in four studies, about 1/10 that for the conversion of E₁S to estrone. Transfer factors were then calculated using these conversion ratios and values for MCR_{E₂} and MCR_{E₁S} either measured in the same subject (Table V) or using average values from our laboratory (Table II) (3). The transfer factor ($\rho^{E_1SE_2}$) averaged 0.014 (range 0.010–0.019) (Table III).

Since E₁S is effective by mouth in contrast to estrone and estradiol, the metabolism of E₁S taken orally to

³H Infusions

Plasma tritium levels			Equilibrium ³ H levels	C ^{E₁E₁S} E ₁ S- ³ H/E ₁ - ³ H	MCR _{E₁}	MCR _{E₁}	ρ ^{E₁E₁S} *
2.75 hr	3.0 hr	3.5 hr					
cpm × 10 ⁻³ /liter			cpm/liter × 10 ⁻³		liter/day	liter/day/m ²	
49.2			45.7	10.3	2290	1350	0.67
123			471				
45.0			44.3	8.68	2180	1400	0.58
142			385				
47.4			46.3	5.34	2140	1310	0.38
83.2			247				
	66.7	67.6	67.2	12.4	1610	1020	0.54
	288	335	833				
				9.18			0.54

plasma E₁S, estrone, and estradiol was studied. When 30 μCi of E₁S-³H was given by mouth, there was a prompt rise in plasma levels of tritiated E₁S, peaking around 1 hr as shown in Fig. 4. Plasma levels of tritiated E₁ and E₂ were 1.0% and 0.1%, respectively, that of E₁S-³H, although E₂-³H was detectable only at 80 min. These values are in close agreement with the conversion ratios found during i.v. infusions of tritiated E₁S shown in Table III.

Conversion of E₁ to E₁S. The data from the estrone-³H infusions are shown in Table IV. Plasma level of the infused estrone became constant in all cases. However, conversion of estrone to E₁S did not reach equilibrium in any infusion, as shown by increasing plasma levels of E₁S-³H. Thus the conversion ratio, could not be calculated directly since equilibrium conditions were not met. Estimates of equilibrium values for estrone-3-sulfate and hence conversion ratios, C^{E₁E₁S}, were calculated using the formula,

$$C^{E_1E_1S} = \frac{E_1S_{t_x} - {}^3H}{(E_1 - {}^3H)(1 - e^{-\gamma T_x})}, \quad (\text{see Appendix})$$

where E₁-³H is the equilibrium value for E₁-³H during E₁-³H infusions and E₁S_{t_x}-³H is the plasma level of tritium in E₁S at time T_x; *e* is the natural logarithm, T_x is the time after beginning the infusion; and γ is the fractional pool turnover of E₁S per unit time. In subject 8, γ was measured directly and average values for γ from Table II were used for subjects 11–13. In one subject, No. 18, in whom MCR_{E₁}, MCR_{E₁S}, and plasma levels of all estrogens had been measured, the SAAM program of Berman and Weiss (12) was used to perform a computer simulation and calculate equi-

librium values for E₁S during a short E₁ infusion. There was agreement between this value and that obtained by the extrapolation shown above.

The average of four determinations of C^{E₁E₁S} in plasma was 9.2 (range 5.34–12.4) (Table IV). Transfer factors were calculated using the conversion ratios, measured values for MCR_{E₁}, and average male and female MCR_{E₁S} from Table I (an MCR_{E₁S} was measured

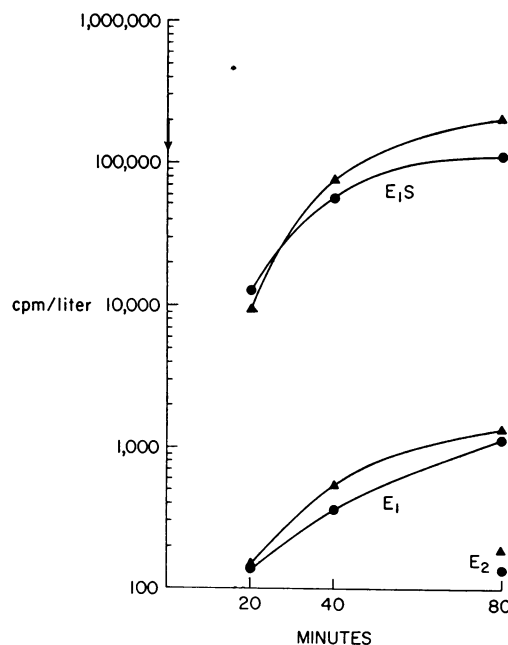


FIGURE 4 Plasma levels of tritium in E₁S; estrone (E₁), and estradiol (E₂) after oral administration of E₁S-³H at time 0 (subjects 1 and 2).

TABLE V
Estradiol-6, 7-

Subject	Sex and age	Estradiol- ³ H infusion	³ H-steroid	Plasma tritium levels			
				1.75 hr	2.0 hr	2.25 hr	2.75 hr
		<i>cpm/day × 10⁻³</i>			<i>cpm × 10⁻³/liter</i>		
7	F 18	1.32	E ₂		111		
			E ₁ S		206		
9	F 22	0.919	E ₂				
			E ₁ S				
15	F 22	1.27	E ₂	140	129	136	148
			E ₁ S	106	111	122	154
16	M 26	1.14	E ₂	69.3	73.2	72.1	
			E ₁ S	26.7	—	38.9	
17	M 26	1.06	E ₂	58.1	58.9	62.6	
			E ₁ S	135	167	211	
18	M 23	1.26	E ₂	60.1	60.9	64.9	
			E ₁ S	78.4	79.2	100	
Mean							

* Value for CMR_{E₁S} performed in the same patient (Table II) used for calculation of ρ ; otherwise average values for our laboratory used (Table III).

and used for calculations in subject 8). The transfer factor ($\rho^{E_1E_1S}$) averaged 0.54 (Table IV).

Conversion of E₂ to E₁S. The data obtained from estradiol-6,7-³H infusions are shown in Table V. Plasma levels of the infused steroid, estradiol, were at equilibrium in all cases, but as with E₁ the conversion of E₂ to E₁S did not reach equilibrium. The extrapolation to equilibrium values was performed as for E₁. Again, the SAAM program of Berman and Weiss (12) was used to confirm the validity of the estimates of equilibrium values calculated by the above formula. This was done in subject 7 in whom we had sufficient data about MCR and plasma estrogen concentrations to allow the computer to derive equilibrium solutions. There was good agreement between the two methods.

The average of six determinations of C^{E₂E₁S} is 7.1; range 2.19–13.6) (Table V). Transfer factors were calculated using these conversion ratios, actual measured values for MCR_{E₂}, and average male and female values for MCR_{E₁S} from Table I (MCR_{E₁S} was measured and used in the calculation of transfer factor in subjects 7 and 9). The transfer factor ($\rho^{E_2E_1S}$) averaged 0.65 (Table V).

DISCUSSION

Estrone sulfate was identified in urine over 30 years ago but little is known of its role in the estrogen economy of the body. Although urinary estrogens are generally excreted as the glucuronide conjugates, in an occasional

subject (13, 14). E₁S has been the major urinary estrogenic metabolite. As Purdy et al. (2) showed, it is also the major plasma metabolite of estradiol. We had postulated that there was a large plasma compartment that slowly exchanged with plasma estrone and estradiol (3), and it seemed likely that this was E₁S. This and the lack of information concerning origin, clearance rates, and metabolism of E₁S prompted the studies reported here.

The MCR_{E₁S} was obtained by fitting the data obtained after rapid injection of E₁S-³H to a straight line thereby assuming a one-compartment model. Frequent samples were not obtained during the first hr so that a rapid component of the disappearance curve would have been missed. In two studies, the 30 min sample suggested an early faster component but this could exert little effect on the calculation of the MCR since the total rate of removal of E₁S from plasma is so slow. The study in subject 6 directly compared the MCR obtained assuming distribution into a single compartment and that obtained during constant infusion when plasma concentrations of E₁S-³H were at equilibrium. Since results obtained by the latter method are independent of the compartmental distribution of the isotope, the agreement between these data is validation of our measurement of MCR_{E₁S}. In the single study of the clearance of DHS, a one-compartment model also was adequate to explain the distribution of the steroid (15). The estimated MCR_{E₁S} of 150 liter/day is in agreement with

³H Infusions

Plasma tritium levels				Equilibrium ³ H levels	CE ₂ E ₁ S E ₁ S- ³ H/E ₂ - ³ H	MCR _{E₂}	MCR _{E₂}	ρE ₂ E ₁ S*
3.0 hr	3.5 hr	5.0 hr	7.0 hr					
<i>cpm × 10⁻³/liter</i>				<i>cpm/liter × 10⁻³</i>		<i>liter/day</i>	<i>liter/day/m²</i>	
111	108			110				
293	318			1210	11.0	1200	739	0.59
58		68	81	74.5				
108		200	275	432	5.8	1230	832	0.81
				138				
				425	3.08	920	520	0.56
				71.5				
				157	2.19	1594	886	0.22
				59.9				
				815	13.6	1770	983	1.20
				62.0				
				414	6.68	2032	1129	0.52
					[7.06]			0.65

data reported recently by Longcope (16) and confirms the early work of Twombly and Levitz (1) who showed that E₁S is cleared from the blood slowly.

The plasma MCR_{E₁S} of 150 liter/day is considerably higher than the plasma MCR of DHS (7 liter/day) (15), and of the blood MCR of DHS (16–30 liter/day) (17), testosterone sulfate (25 liter/day) (17), 17-acetoxypregnenolone sulfate (37 liter/day) (18). A recent report gives values for testosterone sulfate MCR of 75–240 liter/day which are in the same range as our estimates of MCR_{E₁S} (19). However, the fractional pool turnover rate of E₁S of 3.3 pools/day is about the same as the fractional pool turnover rates of other steroid sulfates (15, 17–19). Thus, the higher MCR_{E₁S} must be associated with a larger volume of distribution of E₁S, and in fact its volume of distribution of about 50 liters is higher than those of the other steroids (15, 17, 18) which have lower MCR. Only pregnenolone sulfate had a higher MCR than E₁S but it had a relatively small volume of distribution (7 liters) and a higher fractional turnover rate almost equal to that of some unconjugated steroids (18).

The volume of distribution of the steroid sulfate depends on the binding of the sulfates to plasma proteins, in particular to albumin. Binding to albumin in man has been demonstrated by Puche and Nes (20), Sandberg and Slaunwhite (21), and Plager (22). Puche and Nes, Plager, and Wang and Bulbrook (23) noted that all steroid sulfates tested competed for the

same binding sites. However, the association constants were influenced by the nature of the steroid. The association constant of DHS with albumin has been reported as $0.6\text{--}2 \times 10^5$ liter/mole (20, 22), whereas the E₁S binding constant was estimated at 2×10^4 liter/mole (24). Although these binding affinities were not obtained in the same system, the association of lower affinity constants with higher volumes of distribution is apparent. It therefore seems probable that the clearance rates of the steroid sulfates vary inversely with the tightness of binding to albumin which in turn determines the volume of distribution.

Using the average MCR_{E₁S} and mean E₁S plasma concentrations, we found that plasma production rates of E₁S were similar to those of estrone and estradiol in men and women. Although we have not looked for possible variations of E₁S concentrations throughout the day, it can be shown that they will not vary greatly because of the low fractional pool turnover rate (γ). Thus, the E₁S production rates need not be corrected for a mean plasma E₁S concentration, and should closely approximate the 24-hr production rates of E₁S.

Since sulfokinases are present in peripheral tissues as well as in the gonads and adrenal cortex, we could not know to what extent E₁S was either secreted^a or

^aThe term "secretion" is used to indicate entry of the steroid into the plasma from the glands. The term "production" signifies the rate of entry of the steroid from all sources.

produced from peripheral transformation of plasma precursors. We therefore calculated the contributions of plasma estrone and estradiol to the E₁S production rate. To do this, we used our values for transfer factors, $\rho^{E_1E_1S}$, $\rho^{E_2E_1S}$; $\rho^{E_1SE_1}$, $\rho^{E_1SE_2}$ (Tables II–V) as well as the average transfer factors, $\rho^{E_1E_2}$, $\rho^{E_2E_1}$ (25, 26). The following three equations give solutions for the net amount of steroid entering the plasma from all sources (shown by []) other than from conversion of the two other steroids:

$$\begin{aligned} [E_1] &= PR_{E_1} - \rho^{E_1SE_1}[E_1S] - \rho^{E_2E_1}[E_2], \\ [E_2] &= PR_{E_2} - \rho^{E_1SE_2}[E_1S] - \rho^{E_1E_2}[E_1], \\ [E_1S] &= PR_{E_1S} - \rho^{E_1E_1S}[E_1] - \rho^{E_2E_1S}[E_2]. \end{aligned}$$

Since the production rates (PR) and transfer factors are known, the equations can be solved for the [] values. These values are not true secretion rates since they would include any steroid produced from other precursors. For example, [E₁] would include that estrone derived from plasma androstenedione and testosterone as well as that moiety that is secreted.

The derived data are given in Table VI. For each subgroup, [E₁S] was negative. This means that the production rate calculated to result from conversion of plasma estrone and estradiol is higher than that calculated by direct measurement of the MCR_{E₁S} and plasma E₁S concentration. Hence, there is no need to postulate glandular secretion of E₁S. The lack of correspondence of the data must be explained and serves to point out the many sources of discrepancies in all studies such as this.

The first and most important reason for lack of correspondence in calculations such as these is not really "error" but relates to the large range of normal average values for metabolic clearance rates and transfer factors that are used. Inspection of published data for metabolic clearance rates of E₁ and E₂ (3, 25, 26) reveals not only a large range of values for normals but also for groups of normals studied in the same laboratory (25, 26). This same large range of normal values

is also evident from our data for $\rho^{E_1E_1S}$, $\rho^{E_2E_1S}$, and MCR_{E₁S}. Since our study included only a small sample from a population with a large normal range, it is possible that our average values for $\rho^{E_1E_1S}$, $\rho^{E_2E_1S}$ could be considerably higher than the true mean for the normal population. Agreement between the calculations would be possible only if all parameters were measured in the same normal subjects. Secondly, average values for estradiol concentrations in men reported by us previously (5) and used for our calculations of E₂ production rates are somewhat higher than more recent values of 20–25 pg/ml reported by other laboratories (9–11). The errors in measurement of low estrogen concentrations by radioligand assays tend to cause high values which would result in overestimation of production rates. The consistent finding that estrogen production rates, calculated from dilution of labeled estrogen into urinary metabolites, are smaller than those calculated from the MCR and plasma concentration is further evidence that the latter method overestimates the production rate. Next, the known diurnal variations in plasma estrone concentration (27, 28) and possibly of estradiol, mean that production rates obtained using morning plasma estrogen concentrations will systematically overestimate the 24 hr estrogen production rate of these unconjugated estrogens. Finally, since plasma estradiol and estrone have plasma turnovers of about 50 pools/day and E₁S turnover rate is 3.3 pools/day, plasma concentrations of E₁S will lag behind plasma estrone and estradiol by 6–12 hr. Therefore, it will be difficult to arrive at correct sampling times to estimate the contributions of estrone and estradiol to E₁S production rates.

Since most of the errors discussed will cause overestimation of estrone and estradiol blood production rates, the amount of E₁S calculated to arise from these sources will also be overestimated. Nevertheless, all E₁S found in plasma can be accounted for merely by using mean values \pm standard deviations for production rates and ρ used in the calculations. Hence, it is untenable

TABLE VI
Origin of Estrone Sulfate

	[E ₁]*	$\rho^{E_1E_1S}[E_1]$	[E ₂]	$\rho^{E_2E_1S}[E_2]$	[E ₁ S]	PR E ₁ S (from E ₁ and E ₂)	PR E ₁ S (MCR \times i)
Men	153‡	82.6	74.5	48.5	–54	131	77
Women							
Follicular phase	137	74	157	102	–81	176	95
Women							
Luteal phase	175	94.5	279	181	–94	275	182

* [] = the amount of steroid entering the plasma from all sources other than the two other steroids.

‡ All values are micrograms per day, expressed as E₁S.

to suggest (29) that E₁S may be secreted in amounts sufficient to make it a significant precursor of plasma estrone.

The transfer factor, $\rho^{E_1SE_1}$ of 0.21 was derived from the conversion ratios obtained from the short infusions of E₁S during which plasma levels of E₁S-³H, E₁-³H, and E₂-³H were increasing in four of the five studies. However, $\rho^{E_1SE_1}$ and $\rho^{E_1SE_2}$ appeared to be at equilibrium. The $\rho^{E_1SE_1}$ of 0.21 agrees closely to that of 0.15 reported recently by Longcope (16). The transfer factor, $\rho^{E_1SE_2}$ was only 10% of that for estrone (Table IV). Since $\rho^{E_1E_2}$ is also about 10% (25, 26), it is probable that E₁S reaches the plasma estradiol compartment via plasma estrone. Although the mass of estrone sulfate available for exchange with E₁ is large, about 25–50 μ g (plasma concentration \times volume of distribution), only 5–10 μ g could enter the plasma volume daily as estrone. This is a small fraction of estimated estrone production rates of 40–200 μ g/day in men and women.

Although $\rho^{E_1SE_1}$ and $\rho^{E_1SE_2}$ were apparently at equilibrium, computer simulations of these studies³ using the SAAM program of Berman and Weiss (12) have shown that these conversion ratios cannot be at equilibrium and that the true conversion ratio may be greater by about 15%. Short sampling times and variability in the determinations mask this trend. For the purposes of understanding these facets of estrone sulfate metabolism, the values used in our calculations are sufficiently accurate although they are not equilibrium values.

In contrast to the low biologic potency of orally administered estrone and estradiol, E₁S is an active oral estrogen. Our data confirm that it is rapidly absorbed from the gut and reaches the peripheral circulation without significant metabolism by the liver. Since 0.5 mg of estrone sulfate is an adequate replacement dose for many postmenopausal women, we have calculated that the plasma estrone production rate resulting from this dose is 70 μ g/day ($0.5 \times 0.7 \times 0.2$).⁴ Similarly, the resultant estradiol production rate would be 7 μ g/day. The minimal estrogen production rates that cause either vaginal cornification or endometrial hyperplasia are unknown but Grodin and McDonald⁵ found that an estrone production rate greater than 40 μ g/day (by urinary isotope dilution) induced endometrial hyperplasia in women. The estrone production rate of normal postmenopausal women calculated from plasma concentrations and metabolic clearance rates is about 40 μ g/day (30) and there is little biologic estrogenic effect at these

levels. Thus it may be that the conversion of orally administered estrone sulfate to plasma estrone and estradiol is sufficient to account for its biologic effect. In this regard, it is of interest that Gurpide, Stolee, and Tseng (31) reported that human endometrium rapidly metabolized estrone sulfate to estrone and estradiol.

In summary: (a) E₁S is a major circulating plasma estrogen and has a long plasma half-life; (b) the large contributions of estrone and estradiol to plasma E₁S are more than sufficient to account for all the circulating plasma E₁S; (c) orally administered E₁S is metabolized to plasma estrone and estradiol to the same extent as i.v. administered E₁S.

APPENDIX

Because of the slow fractional turnover rate of E₁S, measurement of $\rho^{E_1E_1S}$ and $\rho^{E_2E_1S}$ at equilibrium values of E₁, E₂, and E₁S was impossible unless infusions were carried out for longer than 24 hr. Since the disappearance of E₁S from plasma can be adequately described by a single exponential, this same single exponential describes the appearance of E₁S in plasma during an infusion of E₁ - ³H or E₂ - ³H. When plasma levels of E₁ - ³H and E₂ - ³H are at equilibrium, a constant amount of E₁ - ³H or E₂ - ³H is being metabolized to E₁S. Thus when estrone or estradiol is infused at rates such that their plasma levels reach equilibrium values, E₁S enters the plasma at a rate equal to the $\rho^{E_1E_1S}$ or $\rho^{E_2E_1S} \times$ the infusion rate of E₁ - ³H or E₂ - ³H. We were therefore able to estimate $C^{E_1E_1S}$, $C^{E_2E_1S}$ during short infusions of either E₁ - ³H or E₂ - ³H by making the following assumptions:

(a) The bolus given before the E₁ or E₂ infusions adequately sets the plasma E₁ - ³H or E₂ - ³H at an equilibrium level that is then maintained by the constant E₁ - ³H or E₂ - ³H infusions. (b) A constant amount of E₁ - ³H or E₂ - ³H is being metabolized to E₁S - ³H from the time 0 when the bolus is given and hence a constant amount of E₁S - ³H is entering the plasma E₁S pool during the entire time of the short E₁ or E₂ infusion. To verify these assumptions, we performed computer simulations of typical E₁ - ³H or E₂ - ³H infusions utilizing the computer model program of Berman and Weiss (12). We were able to show that the dose of E₁ - ³H or E₂ - ³H given as a bolus to begin the short infusions adequately set the plasma level of E₁ - ³H or E₂ - ³H at near equilibrium levels; and that in addition, a constant amount of E₁S - ³H is entering the plasma E₁S pool from the time of the bolus at time 0.

Thus, the instantaneous change in E₁S - ³H is described by the following,

$$\frac{dE_1S_{t_x}}{dt} = k_1E_{1t_x} - \gamma E_1S_{t_x},$$

where E₁S_{t_x} is the instantaneous level of E₁S - ³H at time t_x; E₁ is the instantaneous level of E₁ - ³H at time t_x; k₁ is the fractional turnover of E₁ - ³H to E₁S - ³H; and γ is the total rate of removal of E₁S - ³H as given in Table I. Integrating and solving for E₁S_{t_x} yields,

$$E_1S_{t_x} = \frac{k_1E_{1t_x}}{\gamma} (1 - e^{-\gamma T_x}),$$

where e is natural logarithm; T_x is time after beginning the studies. By definition, however $C^{E_1E_1S} = E_1S - ^3H/E_1 - ^3H$

³ Ruder, H. J., L. Loriaux, M. B. Lipsett, and M. Berman. Manuscript in preparation.

⁴ Dose of E₁S is 0.5 mg/day; the transfer constant, $\rho^{E_1SE_1}$ is 0.2 and only 70% of E₁S is estrone by weight.

⁵ Grodin and McDonald. Personal communication.

when both are equilibrium values. And in fact, $E_{1t_x} - {}^3H$ is at equilibrium from time 0 as explained above and will be written $E_1 - {}^3H$. Hence, $E_{1t_x} - {}^3H = E_1 - {}^3H$. At time $T_x = \infty$, E_1S is also at equilibrium by definition and $e^{-\gamma T_x} = 0$ and yields:

$$E_1S_{\infty} = \frac{k_1E_1}{\gamma} (1 - 0).$$

Rearranging yields:

$$\frac{E_1S}{E_1} = \frac{k_1}{\gamma}.$$

Since $C^{E_1E_1S} = E_1S - {}^3H/E_1 - {}^3H$; $C^{E_1E_1S} = k_1/\gamma$. Thus,

$$E_1S_{t_x} - {}^3H = C^{E_1E_1S} \cdot (E_1 - {}^3H)(1 - e^{-\gamma T_x}).$$

And rearranging:

$$C^{E_1E_1S} = \frac{E_1S_{t_x} - {}^3H}{(E_1 - {}^3H)(1 - e^{-\gamma T_x})}$$

The same formula holds for $C^{E_2E_1S}$ substituting appropriate values for E_2 and γ . All conversion ratios shown in Tables IV and V were calculated using this formula and, where possible, the actual measured value for γ . Otherwise, average values for γ were used from Table I. Since each infusion had at least three plasma samples at different time points, conversion ratios were calculated at each time point during a single infusion and averaged, yielding the values shown in Tables IV and V. Validity of these calculations was confirmed by using data from subjects 7 and 8 in whom we had estimates of all MCR and plasma concentrations for computer simulation using the SAAM program of Berman and Weiss (12). There was close agreement between conversion ratios predicted by the computer program and the conversion ratios calculated by the above formula.

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