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Purification and characterization of human liver dehydroepiandrosterone sulphotransferase

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A form of sulphotransferase capable of sulphating dehydroepiandrosterone and other steroids was purified from cytosol prepared from human liver. Dehydroepiandrosterone sulphotransferase was purified 621-fold when compared with the activity in cytosol using DEAE-Sepharose CL-6B and adenosine 3′,5′-bisphosphate–agarose affinity chromatography. During affinity chromatography, dehydroepiandrosterone sulphation activity could be resolved from *p*-nitrophenol sulphation activity catalysed by phenol sulphotransferase by using a gradient of adenosine 3′-phosphate 5′-phosphosulphate. The purified enzyme was most active towards dehydroepiandrosterone but was capable of conjugating a number of other steroids, including pregnenolone, androsterone and β-oestradiol. No activity towards *p*-nitrophenol or dopamine, substrates for the phenol sulphotransferase, was observed with the pure enzyme. A single band with a subunit molecular mass of 35 kDa was observed by Coomassie Blue staining following SDS/polyacrylamide-gel electrophoresis of the purified enzyme. A molecular mass of 68–70 kDa was calculated for the active form of the enzyme by chromatography on Sephacryl S-200, suggesting that the active form of the enzyme is a dimer.

INTRODUCTION

Sulphotransferases represent a family of enzymes present in the cytosol and membranes of the endoplasmic reticulum and Golgi apparatus of the liver, which are responsible for the conjugation of a wide variety of endogenous and exogenous compounds with sulphate (Mulder, 1981). The sulphotransferases utilize adenosine 3′-phosphate 5′-phosphosulphate as the donor compound for the sulphate moiety and the addition of the charged sulphate to an acceptor compound greatly enhances the excretion of the acceptor compounds into the urine or bile. Sulphate conjugation, therefore, is an important drug metabolism reaction and in most instances the sulphated xenobiotic compounds are biologically inactive.

Sulphate conjugation of hydroxy steroids is considered to comprise a major mechanism for their metabolism and excretion (Mulder, 1981). The major organ involved in the synthesis of most sulphate and glucuronide conjugates is the liver. Although the heterogeneity of sulphotransferases in rat liver is well established (Singer *et al.*, 1976; Jakoby *et al.*, 1980; Sekura *et al.*, 1981), much less is known concerning the number and types of sulphotransferases present in human liver. Purification of several different forms of sulphotransferase from human tissues has been reported (Whittemore & Roth, 1985; Baranczyk-Kuzma, 1986; Heroux & Roth, 1988) including a bile acid sulphotransferase from human liver (Chen & Segel, 1985).

Multiple forms of phenol sulphotransferase activity have been characterized in human liver (Campbell *et al.*, 1987); however, these enzymes have not been purified to homogeneity. The two forms of phenol sulphotransferase activity identified in liver are a monoamine-sulphating form (M-PST) and a phenol-sulphating form (P-PST). The liver forms of P-PST and M-PST are physically and kinetically similar to the platelet forms of these sulphotransferases (Reiter *et al.*, 1983; Campbell *et al.*, 1987; Heroux & Roth, 1988). Dehydroepiandrosterone (DHEA) sulphotransferase activity is also present in human liver (Guglar *et al.*, 1970). Since the PSTs do not sulphate steroids this suggests that DHEA sulphotransferase activity represents a distinct form of sulphotransferase in liver. Characterization of liver DHEA sulphotransferase may therefore provide an insight into the heterogeneity of sulphotransferases in human liver as well as the role of the liver in steroid metabolism. This report describes the purification and characterization of dehydroepiandrosterone (DHEA) sulphotransferase from human liver cytosol. During the purification procedure, DHEA sulphotransferase was resolved from the sulphotransferase responsible for *p*-nitrophenol sulphation (P-PST), the major form of phenol sulphotransferase in human liver (Campbell *et al.*, 1987), confirming that in liver DHEA sulphotransferase is a unique form of sulphotransferase.

EXPERIMENTAL

Materials

Adenosine 3′-phosphate 5′-phosphosulphate (PAPS) and Sephacryl S-200 were purchased from Pharmacia. Adenosine 3′,5′-bisphosphate (PAP), adenosine 3′,5′-bisphosphate–agarose, DEAE-Sepharose CL-6B and

Abbreviations used: DHEA, dehydroepiandrosterone; PST, phenol sulphotransferase; PAP, adenosine 3′,5′-bisphosphate; PAPS, adenosine 3′-phosphate 5′-phosphosulphate.

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steroids were obtained from Sigma. Dehydro[1,2,6,7-^{3}H]-epiandrosterone was from Amersham, and [^{35}S]PAPS was purchased from New England Nuclear. PM30 membranes were obtained from Amicon. All other chemicals were of reagent grade quality.

Sulphotransferase assays

DHEA sulphotransferase reactions routinely contained 50 mM-Tris/HCl, pH 7.5, 10 mM-$MgCl_2$, 3 μM-[^{3}H]DHEA (specific radioactivity 0.05 μCi/nmol) and 20 μM-PAPS. DHEA sulphotransferase activity was maximally active in Tris buffer in the pH range 7.2–7.6. Reactions were terminated by the addition of 3.0 ml of chloroform and 0.25 ml of 0.25 M-Tris/HCl, pH 8.7, was added to alkalinize the solution. The reaction tubes were then vortex-mixed twice for 15 s and centrifuged at 600 *g* for 5 min to separate the aqueous and organic phases. Sulphated DHEA remained in the aqueous phase and the non-conjugated DHEA was extracted into the chloroform phase. Synthesis of DHEA sulphate was then determined by scintillation counting of an aliquot of the aqueous phase.

Phenol sulphotransferase activity was measured using the method of Foldes & Meek (1973) with *p*-nitrophenol as the sulphate acceptor. Reactions routinely contained enzyme solution, 50 mM-phosphate, pH 6.8, and 10 μM-*p*-nitrophenol. Reactions were started by the addition of [^{35}S]PAPS (approx. 0.05 μCi/nmol final specific radioactivity) to a final concentration of 20 μM in a total reaction volume of 0.25 ml.

Preparation of human liver cytosol

Human livers were obtained from the Organ Procurement Program, University of Rochester, immediately after the removal of other donor organs for transplantation. Five normal livers were obtained and were used in the following study. Immediately upon removal from the donor, the livers were chilled on ice and all livers were frozen at −70 °C within 15–30 min of removal. Samples of the livers were thawed in 10 mM-triethanolamine, pH 7.5, containing 1.5 mM-dithiothreitol and 20% glycerol (TEA buffer), minced with scissors and then homogenized with a Brinkman Polytron. Next, the liver suspension was centrifuged at 12000 *g* for 15 min at 4 °C and the supernatant was removed and centrifuged at 100000 *g* for 1 h. The 100000 *g* liver cytosol was recovered and stored frozen at −70 °C. Protein concentrations were estimated using the Bio-Rad protein assay originally developed by Bradford (1976) with bovine serum albumin as a standard.

DEAE-Sepharose CL-6B chromatography of dehydroepiandrosterone and *p*-nitrophenol sulphotransferase activities

Aliquots of human liver cytosol in TEA buffer were thawed on ice and all purification procedures were performed at 4 °C. Approx. 700 mg of liver cytosol protein was applied to a DEAE-Sepharose CL-6B column (2 cm × 16 cm) at a rate of 25 ml/h. After the cytosol had entered the column, approximately 4 column volumes of TEA buffer were applied to the column and this solution was followed by 100 ml of TEA buffer containing 100 mM-NaCl. Sulphotransferase activity was then eluted from the anion exchange column with a linear gradient (600 ml total volume) of 100–225 mM-NaCl in TEA buffer at a flow rate of 25 ml/h. DHEA and *p*-nitrophenol sulphotransferase activities were determined in the fractions. Fractions containing DHEA sulphation activity and relatively low levels of *p*-nitrophenol sulphation activity were pooled and concentrated to approx. 8 ml using an ultrafiltration stirred cell with a PM30 membrane.

The concentrated pool obtained from the DEAE-Sepharose column was then applied very slowly (6–8 ml/h) to an adenosine 3′,5′-bisphosphate (PAP)–agarose affinity column (0.7 cm × 10 cm) previously equilibrated in TEA buffer. The affinity column was washed with 6–7 column volumes of TEA buffer containing 50 mM-NaCl to remove non-specifically bound proteins. DHEA and *p*-nitrophenol sulphotransferase activities were then specifically eluted with a linear gradient (30 ml total volume) of 0–15 μM-PAPS in TEA buffer containing 50 mM-NaCl. No degradation of PAPS was observed during elution of DHEA sulphotransferase from the affinity column.

Gel filtration chromatography of DHEA sulphotransferase

In order to estimate the size of the native active form of DHEA sulphotransferase, concentrated samples of the enzyme following DEAE-Sepharose chromatography were applied to a Sephacryl S-200 column (2.5 cm × 50 cm) equilibrated in TEA buffer containing 100 mM-NaCl. The column had been previously calibrated with commercial molecular mass standards (Sigma). After application of the sample, the column was eluted with TEA buffer at a flow rate of approx. 10 ml/h and 0.9 ml fractions were collected. DHEA sulphotransferase activity was determined in the fractions and the size of the enzymically active protein was estimated by comparison to the elution of the standard proteins.

Gel electrophoresis

Polyacrylamide-gel electrophoresis was performed in the presence of SDS in a Bio-Rad Protean II unit as previously outlined by Laemmli (1970). Samples were pretreated by the addition of β-mercaptoethanol and SDS to final concentrations of 5% and 1%, respectively, and heated to 100 °C for 10 min. Following electrophoresis, the slabs were stained for 2 h in propan-2-ol/acetic acid/water (5:2:13, by vol.) containing 0.05% Coomassie Blue R-250. Slabs were destained with propan-2-ol/acetic acid/water (1:1:8, by vol.). Minimum subunit molecular masses were estimated by comparison with commercial standards (Sigma).

RESULTS

Separation of DHEA and *p*-nitrophenol sulphotransferase activities by DEAE-Sepharose chromatography

Cytosol preparations from several human livers were assayed for their ability to sulphate DHEA and *p*-nitrophenol. Table 1 shows that in cytosol prepared from human liver 2 (HL2), the *p*-nitrophenol sulphation activity was about equal to the DHEA sulphation activity. Also, the DHEA and *p*-nitrophenol sulphation activity in HL2 was substantially lower than the activity detected in the other livers. HL2 was the only tissue obtained from a young child, whereas the other livers were obtained from adults.

Table 1. Sulphotransferase activity in human liver

Cytosol was prepared from samples of the individual human livers as described in the Experimental section. Sulphotransferase activities were determined in at least three different cytosol preparations of each liver. One unit of activity equals 1 nmol of substrate conjugated/min. Values are means ± S.D.

Liver sample (sex, age in years)	Sulphotransferase activity (units/mg of protein)	
	p-Nitrophenol	DHEA
HL 2 (F, 6)	0.185 ± 0.05	0.19 ± 0.01
HL 3 (F, 56)	0.27 ± 0.02	0.27 ± 0.09
HL 4 (F, 55)	0.63 ± 0.07	0.28 ± 0.06
HL 5 (M, 34)	0.38 ± 0.04	0.30 ± 0.04
HL 6 (M, 56)	0.49 ± 0.09	0.37 ± 0.02

Campbell *et al.* (1987) have reported the presence of two types of the phenol-sulphating form of phenol sulphotransferase (P-PST) in human liver, which show slightly different patterns of elution during anion exchange chromatography. Therefore, to characterize our livers as to the type of P-PST they contain, the chromatographic behavior of DHEA and *p*-nitrophenol sulphotransferase activities in the liver samples during DEAE-Sepharose CL-6B chromatography was investigated. Fig. 1 shows the elution patterns of DHEA and *p*-nitrophenol sulphation activity during DEAE-Sepharose chromatography of cytosol from HL2 and HL4. With several different preparations of HL4, the *p*-nitrophenol sulphation activity was always eluted slightly before the DHEA sulphation activity. This separation pattern of the two sulphotransferase activities was also observed with cytosol prepared from HL3, HL5 and HL6 during DEAE chromatography (results not shown). However, during DEAE chromatography of HL2 cytosol, *p*-nitrophenol sulphation activity eluted after the DHEA sulphotransferase activity. This difference in the elution of *p*-nitrophenol sulphotransferase activity is similar to that observed by Campbell *et al.* (1987) (Fig. 1). Since DHEA sulphation activity was better resolved from *p*-nitrophenol sulphotransferase activity during DEAE-Sepharose chromatography of cytosol from HL2, the purification of DHEA sulphotransferase was undertaken with cytosol prepared from this liver. In contrast to the phenol sulphotransferases, no evidence has been obtained to suggest the presence of multiple forms of DHEA sulphotransferase in the small number of human livers available for this study.

Purification of DHEA sulphotransferase by adenosine 3′,5′-bisphosphate–agarose affinity chromatography

Fractions from the DEAE-Sepharose column which contained high levels of DHEA sulphation activity and relatively low levels of *p*-nitrophenol sulphation activity were pooled, concentrated and applied to an adenosine 3′,5′-bisphosphate (PAP)–agarose affinity column. Fig. 2 shows that the *p*-nitrophenol sulphotransferase activity had a greater affinity for the PAP–agarose column than the DHEA sulphotransferase since relatively more *p*-nitrophenol sulphation activity bound to the resin. Elution of the bound sulphotransferases with a gradient of

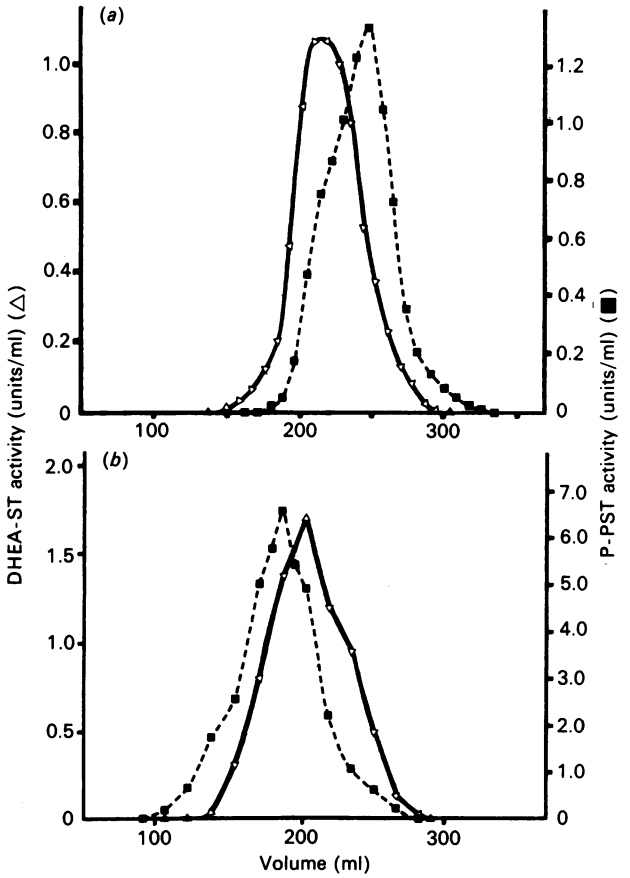

Fig. 1. Separation of DHEA sulphotransferase (DHEA-ST) and *p*-nitrophenol sulphotransferase (P-PST) activities by DEAE-Sepharose CL-6B chromatography

Approx. 700 mg of cytosol prepared from human liver 2 (panel *a*) or human liver 4 (panel *b*) was applied to the anion-exchange column and sulphotransferase activities were eluted as described in the Experimental section using a 100–225 mM-NaCl gradient. DHEA sulphation activity (△—△) and *p*-nitrophenol sulphation activity (■---■) were determined in the fractions. A unit of activity represents 1 nmol of substrate conjugated/min.

PAPS resulted in the elution of DHEA sulphotransferase before the appearance of the sulphotransferase responsible for *p*-nitrophenol sulphation (Fig. 2). This procedure gave a 621-fold purification of DHEA sulphotransferase activity as compared to human liver cytosol and a recovery of approx. 8.1% of the initial DHEA sulphotransferase activity (Table 2). The total recovery of DHEA sulphotransferase activity was 14.1%, if fractions which contain *p*-nitrophenol sulphation activity are also included (Fig. 2).

Pure DHEA sulphotransferase gave a single band with a subunit molecular mass of 35 kDa following SDS/polyacrylamide-gel electrophoresis (Fig. 3). Fractions from the affinity column which also contained *p*-nitrophenol sulphotransferase activity showed the presence of an additional 32 kDa protein following SDS/polyacrylamide-gel electrophoresis (Fig. 3).

Characterization of DHEA sulphotransferase

The ability of DHEA sulphotransferase to sulphate a number of different steroids was investigated (Table 3).

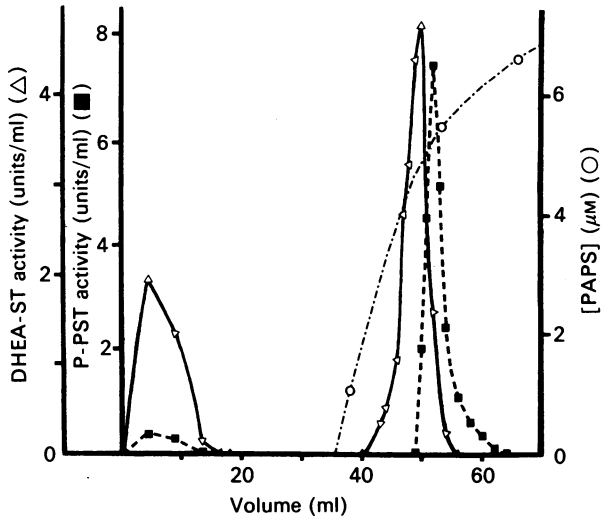

Fig. 2. Elution profile of DHEA sulphotransferase (DHEA-ST) on adenosine 3′,5′-bisphosphate (PAP)–agarose

DEAE fractions from the column in Fig. 1(*a*) that contained DHEA-ST activity were pooled (elution volume 189–241 ml), concentrated by ultrafiltration and applied to a PAP–agarose column (0.7 cm × 10 cm). The column was washed with TEA buffer containing 50 mM-NaCl. Sulphotransferase activities were then eluted with a gradient of PAPS (0–15 μM) (○–·–○) in the same buffer. DHEA-ST activity (△—△) was assayed with DHEA and P-PST activity (■---■) was assayed with *p*-nitrophenol as described in the Experimental section. One unit of activity represents 1 nmol of substrate conjugated/min. PAPS concentration in the fractions was estimated spectrophotometrically at 259 nm using an absorption coefficient of 15400 $M^{-1} \cdot cm^{-1}$.

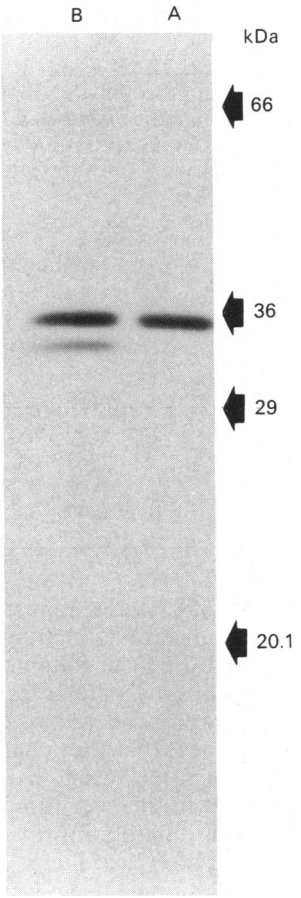

Fig. 3. SDS/polyacrylamide-gel electrophoresis of DHEA sulphotransferase

SDS/polyacrylamide-gel electrophoresis was performed by the method of Laemmli (1970). Lane A contains purified DHEA sulphotransferase (2.5 μg). Lane B contains a fraction after PAP–agarose affinity chromatography which had both DHEA and *p*-nitrophenol sulphotransferase (P-PST) activities. The arrows indicate the position of commercial molecular mass standards (Sigma).

DHEA was the most efficient substrate under the assay conditions utilized. Epiandrosterone and etiocholanolone were sulphated at approx. 80% of the rate of DHEA, whereas pregnenolone was a slightly less efficient substrate. All the steroids tested were sulphated to some extent, including testosterone, which does not possess a hydroxy group at the 3-position. Oestrone, which contains a 3-phenolic group, was the least rapidly conjugated steroid tested (Table 3). The pure enzyme did not conjugate either dopamine or *p*-nitrophenol, which are substrates for the two forms of liver PST.

Although DHEA is the most readily sulphated steroid conjugated by DHEA sulphotransferase, at concentrations of 3 μM or higher substrate inhibition was observed (Fig. 4). Approx. 25% and 33% of DHEA sulphation activity is lost when the DHEA concentration is increased to 10 and 15 μM, respectively. Using DHEA concentrations of 2.5 μM or less, a K_m of approx. 1.6 μM is obtained for DHEA with maximal activity observed at a concentration of about 2.8 μM. Substrate inhibition was also observed using pregnenolone as a substrate at concentrations above 4 μM.

Table 2. Purification of human liver DHEA sulphotransferase

One unit of activity represents 1 nmol of substrate conjugated/min.

Purification step	Protein (mg)	Total activity (units)	Specific activity (units/mg of protein)	Recovery (%)	Purification (fold)
Cytosol (HL 2)	725	155	0.21	100	1.0
DEAE-Sepharose CL-6B	67	78	1.17	50.3	5.5
PAP–agarose	0.095	12.6	133	8.1	621

Table 3. Reactivity of DHEA sulphotransferase with various steroids

Steroid sulphation activity of DHEA sulphotransferase was assayed by the method of Foldes & Meek (1973) using [^{35}S]PAPS as the sulphate donor. Reactions contained 10 μM of the steroid substrate, 20 μM-PAPS, 10 mM-$MgCl_2$ and 50 mM-Tris/HCl, pH 7.5. All assays also contained 2% propylene glycol. Blank reactions contained only propylene glycol. Results are reported relative to DHEA sulphation activity and represent the means ± S.D. of at least three assays. Formation of steroid sulphate esters was confirmed with the Ecteola-cellulose chromatography procedure described by Whittemore & Roth (1985).

Steroid	Relative DHEA sulphotransferase activity (mean ± S.D.)
Dehydroepiandrosterone (3β-hydroxy-5-androsten-17-one)	100
Pregnenolone (3β-hydroxy-5-pregnen-20-one)	60.3 ± 3.0
Epiandrosterone (3β-hydroxy-5α-androstan-17-one)	80.7 ± 7.0
Etiocholanolone (3α-hydroxy-5β-androstan-17-one)	82.0 ± 6.3
Androstenediol (5-androstene-3β,17β-diol)	72.7 ± 4.6
Androsterone (3α-hydroxy-5α-androstan-17-one)	32.8 ± 0.3
β-Oestradiol [1,3,5(10)-oestratriene-3,17β-diol]	13.2 ± 1.1
Pregnene-3β,20α-diol	22.5 ± 1.0
Testosterone (17β-hydroxy-4-androsten-3-one)	13.3 ± 1.5
Oestrone [3-hydroxy-1,3,5(10)-oestratrien-17-one]	7.3 ± 0.6

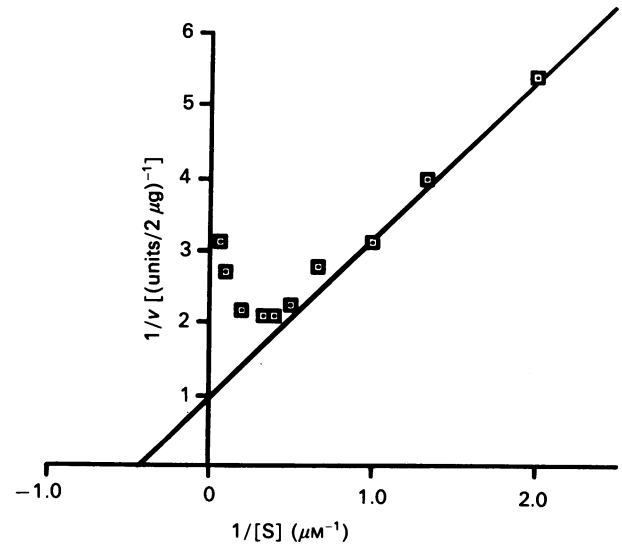

Fig. 4. Substrate inhibition of DHEA sulphotransferase

DHEA sulphation activity of purified DHEA sulphotransferase was determined using concentrations of DHEA varying from 0.5 to 15 μM. The concentration of PAPS in the reactions was 20 μM. One unit of activity equals 1 nmol of DHEA sulphated/min. Each point represents the average of triplicate assays.

To estimate the size of the active form of DHEA sulphotransferase, fractions from the DEAE-Sepharose column containing DHEA sulphation activity were concentrated and applied to a Sephacryl S-200 column equilibrated in TEA buffer containing 100 mM-NaCl. DHEA sulphation activity was eluted from the column at a position with respect to commercial standards which indicates that the enzyme has an active form of approx. 68–70 kDa (results not shown). This would suggest that the active enzyme consists of a dimer of two identical subunits, since only one subunit was observed after SDS/polyacrylamide-gel electrophoresis of the pure enzyme (Fig. 3).

Behaviour of the two sulphotransferase activities on the PAP–agarose affinity column may be related to their kinetic properties. A K_m for PAPS of 1.6 μM was obtained for DHEA sulphation catalysed by DHEA sulphotransferase and a K_i of 1.0 μM was calculated for PAP inhibition of DHEA sulphotransferase activity (results not shown). The K_i for PAP inhibition of P-PST, the *p*-nitrophenol-sulphating form of platelet PST, is 0.1 μM (Heroux & Roth, 1988). The 10-fold higher K_i for PAP inhibition of DHEA sulphotransferase may be responsible for the lower level of binding of DHEA sulphotransferase to the PAP–agarose resin than the *p*-nitrophenol sulphotransferase.

DISCUSSION

This report has established that a unique sulphotransferase is present in human liver which is capable of catalysing the conjugation of a variety of different steroids. DHEA was the most rapidly sulphated steroid; however, all of the steroids tested, including testosterone and oestrone, were conjugated to some degree. This relative lack of specificity for steroid sulphation differs from the high degree of selectivity observed with the different forms of liver UDP-glucuronyltransferase, where the individual enzymes are very specific for the location and orientation of steroid hydroxy groups which are conjugated (Falany & Tephly, 1983; Falany *et al.*, 1986).

Liver DHEA sulphotransferase is also apparently distinct from the partially purified human liver bile acid sulphotransferase described by Chen & Segel (1985). The bile acid sulphotransferase was reported to be inactive in the sulphation of testosterone and oestrone, both of which are substrates for the DHEA sulphotransferase. These authors, however, do not report a subunit molecular mass for the bile acid sulphotransferase for comparison with DHEA sulphotransferase.

Adams & McDonald (1979) have purified an enzyme 245-fold from human adrenal cytosol which is capable of sulphating DHEA; however, their preparation had a specific activity of only 7.3 nmol of DHEA sulphated/min per mg. Following SDS/polyacrylamide-gel electrophoresis both the liver and the adrenal enzymes had subunit molecular masses of approx. 35 kDa and most likely exist as dimers in their native form based on gel exclusion chromatography (Adams & McDonald, 1979). Although several similarities were noted in the physical properties of the liver and adrenal forms of DHEA sulphotransferase, a number of differences were observed in the kinetic properties of the two preparations. In contrast with the findings of Adams & McDonald (1979) with the adrenal enzyme, the liver DHEA sulpho-

transferase did not conjugate epiandrosterone more rapidly than DHEA. Unlike for the liver form of DHEA sulphotransferase, Adams & McDonald (1979, 1981) report that preparations of the adrenal enzyme exhibit non-Michaelis–Menten kinetics with concentrations of DHEA between 0 and 1.0 μM. At higher concentrations of both PAPS and DHEA, these authors report the occurrence of wave-like kinetics with the adrenal DHEA sulphotransferase (Adams & McDonald, 1979, 1980). Similar to the liver enzyme, substrate inhibition has also been reported for a rat liver oestrogen sulphotransferase at steroid concentrations above 2 μM (Sugiyama *et al.*, 1984) and for rat liver hydroxysteroid sulphotransferase 2 at high DHEA concentrations (Marcus *et al.*, 1980).

DHEA sulphate is synthesized and secreted into the circulation in large amounts by the adrenals in humans where it serves as a precursor for oestrogen and androgen synthesis in extra-adrenal tissues. Circulating DHEA sulphate is also the primary precursor for the synthesis of oestrogens in peripheral tissues (e.g. adipose tissue) of post-menopausal women (Grodin *et al.*, 1973). DHEA sulphate has also been implicated in the modulation of a number of important processes in the body including growth, cell differentiation and carcinogenesis (Gorden *et al.*, 1987). The relationship of the DHEA-sulphating activity in the adrenals and DHEA sulphotransferase in human liver is not known. Further characterization of the liver form of DHEA sulphotransferase may therefore provide information on the role of the enzyme in the adrenals as well as the role of sulphation in the metabolism of steroids in the liver.

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