Dehydroepiandrosterone inhibits the amplification of glucocorticoid action in adipose tissue

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Apostolova, Galina, Roberto A. S. Schweizer, Zoltan Balazs, Radina M. Kostadinova, and Alex Odermatt. Dehydroepiandrosterone inhibits the amplification of glucocorticoid action in adipose tissue. Am J Physiol Endocrinol Metab 288: E957–E964, 2005. First published December 21, 2004; doi:10.1152/ajpendo.00442.2004.—Dehydroepiandrosterone (DHEA) exerts beneficial effects on blood glucose levels and insulin sensitivity in obese rodents and humans, resembling the effects of peroxisome proliferator-activated receptor-γ (PPARγ) ligands and opposing those of glucocorticoids; however, the underlying mechanisms remain unclear. Glucocorticoids are reacti-

The importance of the local activation of glucocorticoids in adipose tissue has been demonstrated recently in transgenic mice overexpressing 11β-HSD1 under the adipose-specific AP2 promoter/enhancer (30). These mice expressed approximately threefold higher 11β-HSD1 levels than normal mice. They developed the full metabolic syndrome characterized by visceral obesity, insulin-resistant diabetes, hyperlipidemia, and high arterial blood pressure due to an increased sensitivity to dietary salt and increased plasma levels of angiotensinogen, angiotensin II, and aldosterone (30, 31). Circulating cortico-}

11β-hydroxysteroid dehydrogenase; adipocyte; obesity; diabetes

THE ELEVATED PRODUCTION OF GLUCOCORTICOIDS and activation of glucocorticoid receptor (GR) lead to increased gluconeogene-

sis and antagonize the metabolic actions of insulin. In visceral adipose tissue, excessive glucocorticoids further enhance lipolysis, leading to high levels of free fatty acids, ultimately resulting in the development of insulin resistance and type 2 diabetes (21). 11β-Hydroxysteroid dehydrogenase type 1 (11β-HSD1) plays a crucial role in reactivating inactive glucocorticoids (11-dehydrocorticosterone in rodents, cortisone in humans) to their active forms (corticosterone in rodents, cortisol in humans) (46, 51).

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in adipose tissue was not observed or not evaluated (3, 29, 47). The present findings from studies with transgene animals and inhibitors suggest that a reduced local activation of glucocorticoids in adipose tissue by reducing 11β-HSD1 activity might have beneficial effects in obese and diabetic individuals.

The steroid precursors dehydroepiandrosterone (DHEA) and its sulfated ester (DHEA-S), the most abundant circulating adrenal steroid hormone in humans, are converted by tissue-specific steroidogenic enzymes into active androgens and estrogens in peripheral target tissues (23). Serum concentrations of DHEA and DHEA-S significantly decline with age, and the deficiency of these steroids has been associated with the increasing prevalence of loss of cognitive memory, obesity, insulin resistance, and cardiovascular disease (54). Several studies demonstrated a significant negative association between DHEA and the accumulation of abdominal fat, suggesting that low circulating DHEA is associated with a more central distribution of adipose tissue (8, 9, 53). However, the mechanisms linking obesity, body fat distribution, and serum central distribution of adipose tissue (8, 9, 53). However, the mechanisms linking obesity, body fat distribution, and serum central distribution of adipose tissue (8, 9, 53).

The present findings from studies with transgene animals and inhibitors suggest that a reduced local activation of glucocorticoids in adipose tissue by reducing 11β-HSD1 activity might have beneficial effects in obese and diabetic individuals.

Materials. Cell culture media were purchased from Invitrogen (Carlsbad, CA) and the 3T3-L1 cell line from American Type Culture Collection (Manassas, VA). DHEA, corticosterone, and 11-dehydrocorticosterone were from Steraloids (Wilton, NH). Rosiglitazone was extracted from Avandia tablets (GlaxoSmithKline) using methanol. [1,2,6,7-3H]corticosterone was from Amersham Biosciences (Piscataway, NJ); [11,12,6,7-3H]dehydrocorticosterone was prepared from radiolabeled corticosterone as described previously (37). Reagents for real-time RT-PCR were purchased from Applied Biosystems (Foster City, CA).

Animals and treatments. Written approval for the present experiments was obtained from the Ethical Committee for Animal Research of the University of Berne, Switzerland. Male C57BL/6J mice (20–22 g body wt; Charles River, France) were housed in groups of four in a room maintained on a 12:12-h light-dark cycle. Animals were transferred to individual cages for 2 h and allowed access to 5 g of standard rodent chow. Water was ad libitum. After an adaptation period of 5 days, groups of eight animals were fed for 12 days with control chow or with chow containing either 0.2% DHEA, rosiglitazone at a final dose of 10 mg/kg body wt, or both. Body weight and food and water intakes were recorded daily. One animal of the DHEA group died for unknown reasons, and one animal of the DHEA/rosiglitazone group ate only half of the chow and was excluded from the study. All other animals ate all of the food. Their body weight was comparable and no significant changes were observed during the time of experiment. After 12 days of treatment, mice were killed and the liver and epididymal tissue were removed, washed from contaminating blood with phosphate-buffered saline, blotted on filter paper, snap-frozen in liquid nitrogen, and stored at −70°C until analysis. Serum levels of DHEA-S were measured using the chemiluminescence immunoassay kit and the Immulite One apparatus following the manufacturer’s instruction (Diagnostics Products, Los Angeles, CA).

Cell culture. Murine 3T3-L1 cells were cultured in DMEM supplemented with 10% FCS under nondifferentiating and differentiating conditions in a humidified incubator at 5% CO₂ and 37°C as described previously (49). Briefly, preadipocytes were allowed to achieve 2-day postconfluence and were then subjected to differentiation medium for 2 days (DMEM, 10% FCS, 0.25 mM 3-isobutyl-1-methylxanthine, 0.5 μM dexamethasone, 1 μg/ml insulin). The medium was then replaced with adipocyte growth medium (DMEM, 10% FCS, 1 μg/ml insulin) and 3 days later with DMEM and 10% FCS but in the absence of insulin.

RNA isolation and analysis. Total RNA was extracted from adherent cultured 3T3-L1 cells or from animal tissues after pulverization in liquid nitrogen, homogenization, and lysis as described previously (4). The mRNA levels from different genes were analyzed using an ABI7000 Sequence Detection System. Briefly, reactions were performed in 25-μl vol on 96-well plates, in reaction buffer containing TaqMan Universal PCR Master Mix and 100 ng of cDNA. Specific primers and sequence probes for each gene were obtained as assay-on-demand gene expression products [11β-HSD1, PPARγ coactivator 1 (PGC-1), PPARα, PPARγ, C/EBPα, C/EBPβ, liver X receptor (LXR), leptin, H6PDH] or designed using Primer Express software (C/EBPα; forward, 5′-GGC-3′; reverse, 5′-CCTTTAGACCCATGGAAGT-3′; probe, 5′-ACCCGCCGCCGCC-3′). The data from the analysis of the relative expression of each gene vs. S18 rRNA control probe were determined using the 2^(-ΔΔCt) method (28). Critical threshold (Ct) values were determined from at least four independent cell experiments or from six to eight animals, each measured in triplicate. Results comparable with those with S18 rRNA were obtained when GAPDH was used as a second control probe. Reactions in the absence of reverse transcriptase did not yield a PCR product.

Determination of 11β-HSD1 activity. The oxoreductase activity of 11β-HSD1 was determined by measuring the conversion of 11-dehydrocorticosterone to corticosterone in the presence of radiolabeled 11β,12,6,7-3H]dehydrocorticosterone tracer as described earlier (37). Briefly, radiolabeled 11-dehydrocorticosterone was added to intact differentiated 3T3-L1 cells (7 days after initiating differentiation) at a final concentration of 200 nM. Fully differentiated control adipocytes or adipocytes pretreated for 48 h with various concentra-
tions of DHEA, rosiglitazone, or both were incubated between 1 and 3 h at 37°C with radiolabeled 11-dehydrocorticosterone. The amount of converted 11-dehydrocorticosterone was assessed by ethylacetate extraction of steroids from the growth medium, evaporation of the solvent, followed by separation by thin-layer chromatography and scintillation counting. Alternatively, to assess a potential direct inhibitory effect of DHEA on 11β-HSD1, lysates from human embryonic kidney (HEK)-293 cells stably expressing 11β-HSD1 were incubated in the presence or absence of various concentrations of DHEA, and the conversion of 11-dehydrocorticosterone was determined as described (49). Results were obtained from at least four independent experiments and are expressed as means ± SD.

Statistical analysis. Experiments were performed at least in triplicates and results are expressed as a percentage of means ± SD of control values or as detailed in text. Statistical comparisons between groups were made by ANOVA or unpaired t-tests where appropriate. P < 0.05 was considered significant; *P < 0.01, **P < 0.05.

RESULTS

DHEA-induced downregulation of 11β-HSD1 mRNA expression in 3T3-L1 adipocytes. It has previously been shown that 3T3-L1 cells express high levels of 11β-HSD1 on terminal differentiation to adipocytes (4, 7, 36). Because both the loss of DHEA with age and inappropriately increased 11β-HSD1 expression are associated with altered body fat distribution resulting in accumulation of visceral fat, we hypothesized that DHEA might downregulate 11β-HSD1 activity in adipocytes. To determine the effect of DHEA on 11β-HSD1 gene expression, 3T3-L1 adipocytes were incubated for 48 h with medium alone or in the presence of various concentrations of DHEA. DHEA caused a marked reduction in the expression of 11β-HSD1 mRNA by ~40%, comparable to the effect observed for the known PPARγ agonist rosiglitazone (Fig. 1). Maximal inhibition of 11β-HSD1 mRNA expression on DHEA treatment was observed after incubation at concentrations of 12.5 μM or higher for 24 h and stayed constant for up to 72 h (not shown), again resembling the effects of rosiglitazone (7). Although 11β-HSD1 mRNA levels were most efficiently reduced when a combination of 25 μM DHEA and 10 μM rosiglitazone was used, the effects of DHEA and rosiglitazone were not clearly additive.

DHEA-induced inhibition of 11β-HSD1-dependent oxidation of 11-dehydrocorticosterone in 3T3-L1 adipocytes. We next examined the effect of DHEA on 11β-HSD1 enzyme activity in intact 3T3-L1 adipocytes. Cells were treated with DHEA or vehicle for 48 h, followed by a medium change and determination of the conversion of radiolabeled 11-dehydrocorticosterone to corticosterone in the absence of DHEA. As shown in Fig. 2, 11β-HSD1 oxoreductase activity was significantly and dose dependently decreased on treatment of cells for 48 h with DHEA relative to control cells. Treatment with 100 μM DHEA almost completely inhibited 11β-HSD1 activity. Cytotoxic effects were observed at concentrations higher than 100 μM after incubation for 48 h (not shown). Treatment of differentiated control adipocytes with 100 or 200 μM DHEA for 30 min did not significantly reduce 11β-HSD1 activity, suggesting that the observed inhibition is not due to a general toxic effect. Furthermore, DHEA did not exert a direct inhibitory effect on 11β-HSD1 activity, indicated by the fact that incubation of lysates from HEK-293 cells stably expressing 11β-HSD1 with DHEA did not diminish enzyme activity (IC50 > 50 μM, not shown). Together, these results indicate that DHEA decreases 11β-HSD1 activity by inhibition of gene expression.

Effect of DHEA on the expression of genes associated with the regulation of 11β-HSD1 in 3T3-L1 adipocytes. By having demonstrated that DHEA reduces the expression of 11β-HSD1 in adipocytes, we used quantitative real-time RT-PCR to measure the expression of genes that have been associated with the regulation of 11β-HSD1. PPARα, PPARγ, and LXR, was shown previously to downregulate the expression of 11β-HSD1 on activation (7, 13, 52). Treatment of 3T3-L1 adipocytes with 25 μM DHEA for 48 h differentially regulated the expression of PPARγ (68 ± 15% of untreated control) and PPARα (234 ± 34%) but did not alter the expression of LXR (Fig. 3). Interestingly, PGC-1, known to be a coactivator of several receptors including PPARα, PPARγ, and LXR, was upregulated 2.1-fold. We next measured the effect of DHEA on C/EBPα, which was shown previously to bind directly to the promoter of HSD11B1 and exert a potent stimulatory effect on
but unchanged in liver (108 ± 30%), whereas C/EBPβ was not affected in white adipose tissue (114 ± 25%) but significantly elevated in liver (195 ± 24%). DHEA treatment upregulated PPARα 2.9- and 3.7-fold in white adipose tissue and liver, respectively. In contrast, PPARγ was differentially regulated in white adipose tissue, where it decreased to 68 ± 18%, and liver, where it increased to 294 ± 30%. Interestingly, the effect on PGC-1 mRNA levels was opposite of that on PPARγ with an upregulation to 150 ± 9% in white adipose tissue and 77 ± 18% in liver. LXR did not change in white adipose tissue but increased to 152 ± 8% in liver. In line with the results obtained in 3T3-L1 adipocytes, leptin was significantly downregulated to 27 ± 25% with large interindividual differences. H6PDH mRNA levels were also significantly reduced in white adipose tissue (69 ± 14%) and even more pronounced in liver (39 ± 17%), an effect also observed in animals treated with rosiglitazone (not shown).

**DISCUSSION**

DHEA and glucocorticoids exert opposite effects on cognitive function, blood glucose levels, insulin sensitivity, and body fat distribution; however, a link between the actions of these two steroids remains unclear. Using 3T3-L1 adipocytes and C57BL/6J mice treated with DHEA, we observed a reduced expression and activity of 11β-HSD1, resulting in diminished local amplification of glucocorticoid action. DHEA downregulated 11β-HSD1 in vitro in 3T3-L1 adipocytes and in vivo in liver and white adipose tissue from mice to an extent...
DHEA alters the expression of C/EBP transcription factors

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<td>3T3-L1 cells</td>
<td>0.35±0.11</td>
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<td>1.20±0.30</td>
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<td>Liver</td>
<td>0.60±0.30</td>
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Data represent means ± SD from at least 4 independent cell experiments or from 6–8 animals. C/EBP, CCAAT enhancer-binding protein. 3T3-L1 adipocytes and C57BL/6J mice were treated with dehydroepiandrosterone (DHEA) followed by the determination of mRNA levels using real-time RT-PCR as described in MATERIALS AND METHODS. The mRNA levels were normalized to S18 rRNA control probe and data are expressed relative to the amount of mRNA found in untreated controls (control set as 1).
5) and rosiglitazone (not shown) stimulated PPARγ expression in the liver, resembling the effects reported recently for pioglitazone and glucose on PPARγ expression in HK2 kidney cells (40). An elevated expression of the receptor is expected to elicit a more pronounced response in the presence of an agonist, hence the increased receptor expression could constitute a protective role by preventing inappropriately high levels of 11β-HSD1. In contrast, both DHEA and rosiglitazone treatment resulted in a slight downregulation of PPARγ mRNA in adipose tissue. Whether the DHEA-induced upregulation of PGC-1α in adipose tissue results in a net stimulation of PPARγ receptor response remains to be determined. Decreased PGC-1 expression was found in adipose tissue but not in skeletal muscle from insulin-resistant patients (12). In contrast, PGC-1α is elevated in the liver in fasting and in diabetes and increases hepatic gluconeogenesis (60). Because PGC-1 is regulated in a tissue-specific manner and interacts with several other transcription factors, including LXR and PPARα, the potential effect of each receptor on the expression of 11β-HSD1 is complex.

Furthermore, DHEA may exert a protective effect in adipose tissue and in liver by increasing PPARα expression and preventing excessive 11β-HSD1 levels. In line with a recent study in Wistar rats (20), we observed significantly increased expression of PPARα both in liver and adipose tissue (Fig. 5). The chronic treatment with a PPARα agonist decreased hepatic 11β-HSD1 mRNA (13). Thus some of the anti-diabetic effects of DHEA may be explained by lowering local glucocorticoid action by downregulation of 11β-HSD1. Elevated cortisol concentrations stimulate gluconeogenesis and increase the susceptibility to diabetes. It was also reported that glucocorticoids stimulate PPARα mRNA in hepatocytes by a GR-dependent mechanism, thus there is a negative feedback loop between PPARα and GR. Indeed, transgenic mice overexpressing 11β-HSD1 in the liver exhibited increased PPARα mRNA levels (41). These animals showed an impaired response to high-fat diet with altered lipoprotein assembly and metabolism and a reduced lipoprotein clearance from the circulation and decreased LDL receptor levels. In addition, the induction of major transcriptional regulators of cholesterol homeostasis such as SREBP-2, FXR, LXR, and RXR was attenuated under a high-fat diet. On the other side, mice lacking PPARα accumulated hepatic fat on a normal diet and were prone to obesity (25). They also exhibited increased leptin levels.

DHEA may exert at least part of its effects via leptin. In line with a study in rats (20), we observed a significant decrease in leptin expression in white adipose tissue of DHEA-treated C57BL/6j mice and in murine 3T3-L1 adipocytes after DHEA treatment. Liu et al. (27) reported that the treatment of ob/ob and normal mice with leptin increased hepatic 11β-HSD1 expression and reduced body weight. The leptin-dependent increase in hepatic 11β-HSD1 was mediated by the leptin receptor. The leptin effect on food intake and on body weight is inhibited by glucocorticoids, which may contribute to the development of leptin resistance in obese humans. By downregulating 11β-HSD1, DHEA counteracts the effects of glucocorticoids, which stimulate the expression of the leptin receptor and leptin secretion, thereby antagonizing leptin action. Although the molecular mechanisms underlying leptin action remain unclear, there is increasing evidence for a role of the PI3K pathway. Activation of PI3K by the anorexigenic ciliary neurotrophic factor led to the suppression of leptin expression and secretion (39). Mice deficient in the p85α regulatory subunit of PI3K showed elevated PIP3 production in adipocytes, had enhanced insulin sensitivity and increased serum leptin levels, and exhibited significantly greater increases in body weight and white adipose tissue mass (55). In addition, glucocorticoids rapidly inhibited leptin-induced JAK/STAT pathway, partly via the MAP kinase pathway (16). These observations suggest that the anti-diabetic effect of DHEA may be due, at least in part, by a decrease in leptin levels, possibly by a mechanism involving PI3K.

The DHEA concentrations applied in our study with mice represent pharmacological doses well above physiological concentrations, and species-specific effects have to be considered when trying to extrapolate these results to humans. Whereas a concentration of DHEA-S of 2,400–4,200 ng/ml (6.5–11.4 μM) is found in young human individuals (57), the serum concentrations of DHEA and DHEA-S reported for rodents are highly controversial. Levels of 1,000 ng/ml (2.7 μM) (18) and 2,200 ng/ml (6.0 μM) (33) were measured in C57BL/6 mice, either using radioimmunoassay or liquid-phase kinetics enzyme immunoassay kits. In contrast, we found concentrations of 160 ng/ml (0.43 μM) or below detection limit in untreated animals using chemiluminescence immunoassay, concentrations that are ~20-fold lower than those found in young humans. Even lower levels of DHEA-S were reported in DBA/1J mice (25 nM, determined by gas chromatography/mass spectrometry) (19) and very low concentrations of 0.62 ng/ml (1.7 nM) were detected in Wistar rats (14), indicating significant methodological differences and species-specific variability.

Nevertheless, a recent randomized controlled trial in elderly women and men demonstrated that administration of 50 mg/day of DHEA for 6 mo significantly reduced abdominal visceral fat as well as abdominal subcutaneous fat (57). DHEA treatment also led to a significant increase in insulin sensitivity. In these individuals serum DHEA-S concentrations increased from 700 ng/ml (1.9 μM) to 3,600 ng/ml (9.8 μM), levels found in young humans. Thus supplementation therapy may help to treat the progressive decline of circulating DHEA levels with aging and may prevent elevated intra-adipose cortical levels (or corticosterone in rodents), which antagonize the effects of insulin and induce hyperglycemia and visceral fat accumulation (30, 35).

In conclusion, DHEA downregulates 11β-HSD1 both in the liver and in adipose tissue, thereby inhibiting the local amplification of glucocorticoids. The reduction of H6PDH expression in both tissues may further contribute to the inhibition of the oxoreductase activity of 11β-HSD1 by limiting the availability of its cofactor NADPH. Our results suggest that this DHEA-mediated downregulation of 11β-HSD1 is caused by a switch in the expression from its potent transcriptional activator C/EBPα to the weak activators C/EBPβ and/or C/EBPδ. These findings may explain some of the anti-glucocorticoid effects of DHEA.

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GRANTS
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