Acute effects of thyroid hormones on the production of adrenal cAMP and corticosterone in male rats

MING-JAE LO,1 MEI-MEI KAU,1 YEN-HAO CHEN,2 SHIOW-CHWEN TSAI,1 YU-CHUNG CHIAO,1 JIANN-JONG CHEN,1 CHARLIE LIAW,1 CHIEN-CHEN LU,1 BU-PIAN LEE,1 SI-CHIH CHEN,2 VICTOR S. FANG,3 LOW-TONE HO,3 AND PAULUS S. WANG1

1Department of Physiology, National Yang-Ming University, Taipei 112; 2Department of Biology, Fu-Jen Catholic University, Taipei 242; and 3Department of Medical Research and Education, Veterans General Hospital-Taipei, Taipei 112, Taiwan, Republic of China

Lo, Ming-Jae, Mei-Mei Kau, Yen-Hao Chen, Shiow-Chwen Tsai, Yu-Chung Chiao, J Iann-Jong Chen, Charlie Liaw, Chien-Chen Lu, Bu-Pian Lee, Si-Chih Chen, Victor S. Fang, Low-Tone Ho, and Paulus S. Wang. Acute effects of thyroid hormones on the production of adrenal cAMP and corticosterone in male rats. Am. J. Physiol. 274 (Endocrinol. Metab. 37): E238–E245, 1998.—The acute effects of thyroid hormones on glucocorticoid secretion were studied. Venous blood samples were collected from male rats after they received intravenous 3,5,3'-triiodothyronine (T3) or thyroxine (T4). Zona fasciculata-reticularis (ZFR) cells were treated with adrenocorticotropic hormone (ACTH), T3, T4, ACTH plus T3, or ACTH plus T4 at 37°C for 2 h. Corticosterone concentrations in plasma and cell media, and also adenosine 3',5'-cyclic monophosphate (cAMP) production in ZFR cells in the presence of 3-isobutyl-1-methylxanthine, were determined. The effects of thyroid hormones on the activities of steroidogenic enzymes of ZFR cells were measured by the amounts of intermediate steroid products separated by thin-layer chromatography. Administration of T3 or T4 suppressed the basal and the ACTH-stimulated levels of plasma corticosterone. In ZFR cells, both thyroid hormones inhibited ACTH-stimulated corticosterone secretion, but the basal corticosterone was inhibited only with T3 > 10-10 M and T4 > 10-8 M. Likewise, T3 or T4 of 10-7 M inhibited the basal- and ACTH-stimulated levels of intracellular cAMP. Physiological doses of T3 or T4 decreased the activities of 3β-hydroxysteroid dehydrogenase, 21-hydroxylase, and 11β-hydroxylase. These results suggest that thyroid hormones counteract ACTH in adrenal steroidogenesis through their inhibition of cAMP production in ZFR cells.

3,5,3’-triiodothyronine; thyroxine; zona fasciculata-reticularis cells; P450c11 activity; adenosine 3’,5’-cyclic monophosphate
In vivo experiments: effects of a single injection of thyroid hormones. All rats were anesthetized with ether and catheterized via the right jugular vein (38). They were injected 20 h after the catheterization with saline, T$_3$ (5 µg·ml$^{-1}$·kg body wt$^{-1}$; Sigma Chemical, St. Louis, MO), thyroxine (T$_4$; 20 µg·ml$^{-1}$·kg body wt$^{-1}$; Sigma Chemical), ACTH (5 µg·ml$^{-1}$·kg body wt$^{-1}$), ACTH plus T$_3$, or ACTH plus T$_4$. Blood samples (0.3 ml each) were collected from the jugular catheter at 0, 30, 60, 90, 120, and 180 min after the challenge between 0800 and 1200. The lost blood volume was replenished with heparinized saline immediately after each bleeding.

Plasma was separated by centrifugation at 10,000 g for 1 min and stored at −20°C. The concentrations of total T$_3$ and total T$_4$ in rat plasma were measured by radioimmunooassay (RIA). To measure corticosterone, 0.1 ml plasma was mixed with 1 ml diethyl ether (10 M), vortexed for 20 min, centrifuged at 1,000 g for 5 min, and then quickly frozen in a mixture of acetone and dry ice. The organic phase was collected, dried, and reconstituted in a buffer solution (0.1% gelatin in phosphate-buffered saline (PBS), pH 7.5) before the concentration of corticosterone was measured by RIA.

Preparation of zona fasciculata-reticularis cells for cell culture. An adrenocortical preparation enriched with zona fasciculata-reticularis (ZFR) cells for culture was performed following a method described by Purdy et al. (26) in 1991 with minor modifications. Male Sprague-Dawley rats were decapitated. The adrenal glands were rapidly excised and stored in an ice-cold 0.9% NaCl solution. The adipose tissues were removed. The encapsulating glands were separated into capsule (mainly zona glomerulosa) and inner zone (mainly ZFR) fractions with forceps. The fractions of inner zone from 10–20 adrenals were incubated with collagenase (2 mg/ml, Sigma Chemical) at 37°C in a shaking water bath, 100–110 strokes/min, for 60 min. The collagenase was dissolved in 2–4 ml of Krebs-Ringer bicarbonate buffer (3.6 mmol K$^+$, 1.16 mmol Mg$^{2+}$, 1.16 mmol Ca$^{2+}$, 3 mmol Na$^+$, 7 M), T$_4$ (10 M), ACTH, and 11-DOC (10 M). With this antiserum (PSW4–9) an RIA was established for the measurement of plasma corticosterone levels. In this RIA system, a known amount of unlabeled corticosterone, an aliquot of plasma extract, or media samples adjusted to a total volume of 0.2 ml by a buffer solution (0.1% gelatin-PBS, pH 7.5) was incubated with 0.1 ml corticosterone antiserum (1:16,000 dilution) diluted with 0.1% gelatin-PBS and 0.1 ml $[^{3}H]$corticosterone ($-8,000$ counts/min (cpm); Amersham International) at 4°C for 24 h. Duplicate standard curves with 6 points ranging from 2.5 to 1,200 pg of corticosterone were included in each assay. An adequate amount (0.2 ml) of 0.25% dextran-coated charcoal (Sigma Chemical) was then added with further incubation in an ice bath for 15 min. At the end of the incubation period, the assay tubes were centrifuged at 1,000 g for 15 min. The supernatant was mixed with 3 ml of liquid scintillation fluid (Ready Safe, Beckman) before the radioactivity was counted in an automatic beta counter (Wallac 1409, Pharmacal, Turku, Finland). The sensitivity of corticosterone RIA was 5 pg assay tube. The inhibition curves produced by ether-extracted rat plasma and the incubation medium of rat adrenal glands were parallel to the curve of unlabeled corticosterone (Fig. 1). The cross-reactivities were 12% with 11-DOC, 1% with 11-dehydrocorticosterone, 0.3% with aldosterone, and <0.2% with 18-hydroxydeoxycorticosterone, progesterone, estradiol, and testosterone. The intra- and interassay coefficients of variation were 3.3% (n = 5) and 9.2% (n = 4), respectively.

RIA of cAMP. The concentration of adrenal cAMP was determined by RIA as described elsewhere (17, 36). With the anti-cAMP serum no. CV-27 pool, the sensitivity of cAMP was 2 fmol assay tube. The intra- and interassay coefficients of variability were 6.9% (n = 5) and 11.9% (n = 5), respectively.

Fig. 1. Dose-response curve for corticosterone standard, incubation medium of zona fasciculata-reticularis (ZFR) cells, and extract of rat plasma after log-log transformation. B/Bo, ratio of binding of $[^{3}H]$corticosterone in the presence of unlabeled corticosterone to maximal binding of $[^{3}H]$corticosterone with anticorticosterone antibody.
Activities of 3β-hydroxysteroid dehydrogenase, 21-hydroxylase, and 11β-hydroxylase. ZFR cells (1 x 10⁶ per tube) were preincubated for 60 min at 37°C in 95% O₂-5% CO₂ in 1 ml KRBA medium. After centrifugation at 200 g for 10 min, the supernatant was discarded, and the cells were incubated for 60 min in tubes in 0.2 ml KRBA containing pregnenolone (10⁻⁹ M) and [³H]pregnenolone (8,000 – 10,000 cpm, 4.5–5.0 pmol, NEN-Du Pont) or DOC (10⁻⁹ M) and [¹⁴C]DOC (18,000–20,000 cpm, 1.8–2.0 nmol; NEN-Du Pont) in the presence or absence of hormones, such as T₃ (10⁻¹¹–10⁻⁹ M) or T₄ (10⁻⁹–10⁻⁷ M). At the end of incubation, the medium containing radioactive products was removed from cultures by centrifugation at 200 g for 10 min. The media were extracted with 5 volumes of diethyl ether, shaken for 30 min, centrifuged at 200 g for 3 min, and then quickly frozen in a mixture of acetone and dry ice. The organic phase was collected, dried, and reconstituted in 100% ethanol. Aliquots of 50 µl of each sample and 5 µl of unlabeled carrier steroids (1 mg/ml) were spotted on silica gel G sheets containing a fluorescent indicator (Macherey-Nagel, Düren, Germany) and chromatographed in a carbon tetrachloride-acetone (4:1, vol/vol) solution. The sheets were dried, and steroid-containing spots were located under ultraviolet light. The radioactive products was removed from cultures by ether extraction and thin-layer chromatography (TLC) was 54%.

Statistical analysis. The treatment means of both in vivo and in vitro studies were tested for homogeneity using analysis of variance (ANOVA), and the difference between specific means was tested for significance using Duncan's multiple range test (33). A difference between two means was considered statistically significant when P was <0.05.

RESULTS

Effects of intravenous injection of T₃ and T₄ on plasma total T₃ and total T₄. A single intravenous injection of T₃ or T₄ increased plasma concentrations of T₃ (35-fold) or T₄ (9-fold) at 30 min after injection compared with the basal level in the same group (P < 0.01; Fig. 2, top and bottom). The levels of plasma T₃ or T₄ in T₃- or T₄-injected rats increased significantly from 30 to 180 min after injection compared with the saline-injected animals (P < 0.01), respectively (Fig. 2, top and bottom).

ACTH plus T₃ or ACTH plus T₄ significantly increased plasma T₃ or T₄ concentration at 30, 60, 120, and 180 min after injection compared with the corresponding basal levels in the same group (P < 0.01; Fig. 2, top and bottom). After injection of ACTH plus T₃ or ACTH plus T₄, plasma T₃ or T₄ concentrations from 30 to 180 min were significantly higher than those in ACTH-injected animals (P < 0.01; Fig. 2, top and bottom).

Effects of intravenous injection of T₃ and T₄ on plasma corticosterone. A single intravenous injection of T₃ significantly decreased plasma corticosterone at 30, 120, and 180 min after injection compared with the basal level in the same group (P < 0.01; Fig. 3, top).

![Fig. 2. Effects (means ± SE) of a single iv injection of 3,5,3'-triiodothyronine (T₃), adrenocorticotropic hormone (ACTH), or ACTH plus T₃ on concentration of plasma total T₃ (top), and those of thyroxin (T₄), ACTH, or ACTH plus T₄ on concentration of plasma total T₄ (bottom). Male rats were iv injected with saline, T₃ (5 µg/kg), T₄ (20 µg/kg), ACTH (5 µg/kg), ACTH plus T₃, or ACTH plus T₄ via the right jugular vein. Blood samples were collected through a jugular catheter at times indicated. ★★P < 0.01 vs. saline-injected rats. ++, +++P < 0.05, P < 0.01 vs. value at 0 min, respectively.](http://ajpendo.physiology.org/DownloadedFrom/10.2203.32.247)
Three hours after injection of T3, plasma corticosterone diminished significantly compared with the saline-injected animals (P < 0.01; Fig. 3, top).

Thirty minutes after a single injection of ACTH, the plasma corticosterone levels responded with a 4.3-fold increase (from 20.6 ± 3.6 to 90.5 ± 8.4 ng/ml; Fig. 3, bottom). Administration of both ACTH and T3 significantly reduced (P < 0.05 or P < 0.01) the corticosterone response between 30 and 120 min after injection compared with the ACTH-stimulated group (Fig. 3, bottom).

One hundred eighty minutes after intravenous injection of T4, the plasma corticosterone levels responded with a 2.5-fold decrease (from 17 ± 1.9 to 6.7 ± 1.4 ng/ml; Fig. 4, top) compared with the basal level in the same group. A single intravenous injection of T4 significantly decreased plasma corticosterone at 120 and 180 min after injection compared with the saline-injected group (P < 0.05 or P < 0.01; Fig. 4, top).

From 30 to 90 min after injection of ACTH plus T4, significantly diminished plasma corticosterone was noted compared with the level of the group treated with ACTH alone (P < 0.05 or P < 0.01; Fig. 4, bottom).

Effects of T3 and T4 on the release of corticosterone in vitro. ACTH stimulated the production of corticosterone for 120 min in ZFR cells in a dose-dependent manner (Fig. 5). The increase was already significant (6.6-fold) at a dose of 10^{-10} M and reached an ~15.5-fold increase at a dose of 10^{-8} M.

Incubation of either T3 (10^{-9}-10^{-7} M), T4 (10^{-7} M) alone, or T3 or T4 in combination with ACTH (10^{-8} M) significantly (P < 0.01) decreased the release of corticosterone from ZFR cells compared with the vehicle or ACTH-treated groups, respectively (Fig. 6).

Forskolin (10^{-6} M) caused a 3.5-fold rise in corticosterone production. Administration of T3 (10^{-11}-10^{-9} M) or
T4 (10^{-8} M, 10^{-7} M) significantly lowered the forskolin-stimulated production of corticosterone in ZFR cells (Fig. 7).

Administration of ZFR cells for 120 min by DOC (10^{-8} M) in combination with T3 (10^{-9} M) or T4 (10^{-9}-10^{-8} M) significantly (P < 0.05 or P < 0.01) decreased the release of corticosterone compared with the DOC-treated group (Fig. 7).

Effects of T3 and T4 on the in vitro production of cAMP in response to IBMX. The levels of extracellular (i.e., medium) and intracellular (i.e., cell) cAMP after incubation of rat ZFR cells with 0.5 mM IBMX are illustrated in Fig. 8. T3 and T4 did not alter the basal levels of extracellular cAMP (Fig. 8, top). T3 and T4 at 10^{-7} M decreased the basal levels of intracellular cAMP (Fig. 8, bottom) and the stimulatory effect of ACTH on the levels of both extra- and intracellular cAMP. Low doses of T3 (10^{-9} and 10^{-8} M) or T4 (10^{-8} M) did not alter the basal levels but attenuated the ACTH-stimulated levels of both extra- and intracellular cAMP.

Effects of T3 and T4 on the activities of 3β-HSD, 21-hydroxylase, and 11β-hydroxylase. Incubation of both T3 (10^{-10} M or 10^{-9} M) and T4 (10^{-9}-10^{-7} M) in combination with DOC (10^{-9} M) and [14C]DOC (1.8–5.0 pmol) for 60 min markedly decreased 11β-hydroxylase activity (expressed as the ratio of [14C]corticosterone/[14C]DOC) from 22 to 63% compared with the control group (Fig. 9).

Administration of ZFR cells for 60 min with T3 (10^{-10} M) or T4 (10^{-9}-10^{-8} M) in combination with pregnenolone (10^{-9} M) and [3H]pregnenolone (4.5–5.0 pmol) resulted in a decline (between 49 and 66% in 3β-HSD activity (Fig. 10, top) and 28–30% in both 3β-HSD and 21-hydroxylase activities (Fig. 10, middle)). T3 and T4 caused about 14% inhibition (P < 0.01) in 3β-HSD, 21-hydroxylase, and 11β-hydroxylase activities (Fig. 10, bottom).

DISCUSSION

It has been demonstrated that chronic administration of T3 in low doses (8 µg) decreases the levels of plasma and adrenal corticosterone (7). Our data indicate...
These results reflect that the thyroid hormones, T3 and T4, exert an acute inhibitory effect on both the basal and the ACTH-stimulated secretion of corticosterone. The disagreement between past and present findings might be due to the different methods for hormone measurement (the previous fluorometric assay vs. the present RIA) and/or the duration for observations (the previous chronic vs. the present acute). Chronic administration of T3 at high concentrations (25–40 µg) in rats induces an increase in plasma corticosterone and adrenal hypertrophy, indicating intense stimulation of adrenal cortical function in chronic, severe hyperthyroidism (7). It has been reported that the effect of in vivo T4 on adrenocortical secretion is related to the duration of treatment (4). Thyroid hormones have also been proposed to play a role in the maintenance of biological rhythms (32). It has been found that the amplitude of the circadian rhythm of blood corticosterone levels gradually decreases with time after thyroidectomy, and daily treatment with T3 or T4 for 2 wk restores the amplitude of the circadian adrenocortical rhythm to prethyroidectomized levels (22). Moreover, the plasma corticosterone response to corticotropin-releasing hormone (CRH) stimulation is increased, even though the response to ACTH is decreased, in rats administered chronically with pharmacological doses of T4 compared with euthyroid rats (14). These results reflect the fact that chronic deficiency or administration of thyroid hormones causes a complicated effect on the hypothalamus-pituitary-adrenal (HPA) axis.

It has been known that PTU-induced hypothyroidism causes a significant reduction in CRH gene transcripts in the paraventricular nucleus and reduces both anterior pituitary proopiomelanocortin expression and circulating corticosterone in the rat (30). The circulating levels of thyroid hormones have a major effect on the central regulation of the HPA axis (30). Our data indicate that acute administration of T3 or T4 evokes an inhibitory rather than a stimulatory effect on corticosterone secretion in rat ZFR cells. These results are in agreement with the observation by Sanchez-Franco et al. (29) in propylthiouracil (PTU)-treated rats. The reasons for these differences are unclear. Because the plasma ACTH remained unchanged in the PTU-treated rats and no data regarding T4 replacement in PTU-induced hypothyroid rats were presented (29), we suspect that the reduction of plasma corticosterone may be due to the toxic effect of PTU on the adrenal gland. Recently, we found that the administration of PTU (1 mg/ml) inhibited both basal and ACTH-stimulated production of corticosterone in rat ZFR cells by 57 and 94%, respectively (unpublished data).

Although high post-ACTH levels of plasma corticosterone found in thyroid-treated animals compared with controls have been attributed to a reduction in the volume of distribution of corticosterone in the thyroid-treated animals (34), our results indicated that the thyroid hormones exert an acute inhibitory effect on the basal and the ACTH-stimulated secretion of corticosterone. These results are in agreement with the observations by Moore and Callas (19), who found that drastic mitochondrial alterations characterized the zona fasciculata of hyperthyroid rats, suggesting that thyroid hormones may act.
directly on adrenal fasciculata cells. Boler and Moore (4) observed that the suppression of adrenocortical steroidogenesis produced by thyroid hormone is related to a mitochondrial effect, although the mechanism is unknown. The inhibition of postpregnenolone steroidogenic enzymes in response to T3 and T4 (Figs. 9 and 10) reflects a strong correlation between decreased steroidogenesis (including 3α-HSD, 21-hydroxylase, and 11β-hydroxylase activities) and the inhibition of corticosterone production in ZFR cells after administration of T3 or T4.

It has been shown that the rat genome contains four P450c11 genes (CYP11β1, CYP11β2, CYP11β3, CYP11β4). One of these (CYP11β1) encodes P450c11β, which is the steroid 11β-hydroxylase found solely in ZFR cells and is responsible for the conversion of 11-DOC to corticosterone (18). However, the regulation of P450c11β1 mRNA expression by thyroid hormones in rats is not known. Our results indicated that T3 and T4 inhibit the stimulatory effect of DOC on corticosterone release (Fig. 7) and the 11β-hydroxylase activity (Figs. 9 and 10) in ZFR cells. During the last decade, the specific T3 receptors have been identified in rat FRTL 5 thyroid follicular cells (1), in anterior pituitary GH cells (6), and in human luteinized granulosa cells (10). Although the thyroid hormone receptor has not been identified in rat adrenocortical cells, it is probable that T3 or T4 acts on the ZFR cells via specific thyroid hormone receptors.

Simonian demonstrated that T3 alone had no effect on 3α-HSD activity in human fetal adrenal cell cultures for 48 h (31). However, treatment with maximal concentrations of 10 nM ACTH plus 1 nM T3 increased the 3α-HSD activity an additional 59–115% over that for ACTH alone (31). Our results indicated that thyroid hormones alone inhibit the 3α-HSD activity of adrenocortical cells in the adult rat. The reasons for the different observations are not known at the present time, but they may be attributable to development, species, or treatment duration. It has been shown that use of adrenal homogenates or mitochondria from euthyroid animals indicates that T4 also suppresses some phases of corticoid conversion (13) and inhibits 11β-hydroxylase (25) and the adrenal transhydrogenase enzyme (24). It has been reported that thyroidectomy for 8 wk slowed down the activity of microsomal 21-hydroxylase and mitochondrial 11β-hydroxylase by ~30% (3). The absence of thyroid hormone may decrease the transmembrane gradient of the H ions that drive ATP and NADPH synthesis, which are both coupled to electron transport chain function (8). This observation, however, was not in agreement with the results by Freedland and Murad (8), which showed a significant increase in mitochondrial malic enzyme activity after in vitro T3 administration. The direct effect of thyroid hormones on adult rat ZFR cells and the activities of steroidogenic enzymes have not been previously investigated. We found a marked inhibitory effect of T3 and T4 on postpregnenolone steroidogenic enzymes, including 3α-HSD, 21-hydroxylase, and 11β-hydroxylase activities. These findings are in agreement with the results reported by Peron et al. (25).

ACTH regulates glucocorticoid production by acting on specific receptors in the adrenal cortex. The number of ACTH binding sites in adrenocortical cells is increased by exposure of these cells to the activators of the cAMP pathway, e.g., dibutyryl cAMP or forskolin (20). In the present study, we found that the stimulatory effects of ACTH on both plasma corticosterone and corticosterone production in vitro were diminished by T3 and T4. T3 and T4 attenuated the stimulatory effects of corticosterone release in ZFR cells by adenylyl cyclase agonist and forskolin and decreased the stimulatory effects of ACTH on cAMP production, indicating that cAMP mediates this regulatory mechanism. Because T3 at 10−9 M inhibited ACTH-induced release of corticosterone (Fig. 6) but did not alter the level of extracellular cAMP (Fig. 8), we suggest that the cAMP response element was not the only pathway of the inhibition of corticosterone production by thyroid hormones. ACTH receptor genomic DNA has been isolated in the human (21), bovine (27), and mouse (16). Whether thyroid hormones alter the gene expression of the ACTH receptor in rats is not known but is worth investigating.

In summary, these findings suggest that acute administration of thyroid hormones 1) inhibits the secretion of corticosterone, both in vivo and in vitro; 2) attenuates the stimulatory effects of ACTH on the secretion of corticosterone via a decrease of cAMP production in ZFR cells; and 3) decreases the activities of 3α-HSD, 21-hydroxylase, and 11β-hydroxylase in ZFR cells. These results may contribute to the characterization of the regulatory mechanisms of adrenocortical function by thyroid hormones. Although the in vitro effect of thyroid hormones is fast, whether the inhibition of thyroid hormones on steroidogenesis in ZFR cells is mediated by nuclear receptor mechanisms is not clear at the present time. Furthermore, the inhibitory effects of T3 and T4 on corticosterone secretion might be of interest in the therapy of patients with hypercortisolism caused by primary hypothyroidism.

The authors greatly appreciate Dr. C. Weaver’s English editing. This study was supported by Grant NRICM-85104 from the National Research Institute of Chinese Medicine; Grant VGHYM-86–S4–19 from the VGH-NYMU Joint Research Program; Tsou’s Foundation, ROC; a grant from the Veterans General Hospital-Taipei; NSC 86–2314-B-010–074 from the National Science Council; and an award from the Medical Research and Advancement Foundation in memory of Dr. Chi-Shuen Tsou, ROC, to P. S. Wang. Address for reprint requests: P. S. Wang, Dept. of Physiology, National Yang-Ming Univ., Shih-Pai, Taipei, Taiwan, Republic of China.

Received 18 March 1997; accepted in final form 29 October 1997.

REFERENCES


