Effects of arecoline on testosterone release in rats

Shyi-Wu Wang,1* Guey-Shyang Hwang,2,3 Te-Jung Chen,2 and Paulus S. Wang2*

1Department of Physiology and Pharmacology, Chang Gung University, Taoyuan; 2Department of Physiology, School of Medicine, National Yang-Ming University, Taipei; and 3Department of Nursing, Chang Gung Institute of Technology, Taoyuan, Taiwan, Republic of China

Submitted 23 January 2008; accepted in final form 16 June 2008

Wang S-W, Hwang G-S, Chen T-J, Wang PS. Effects of arecoline on testosterone release in rats. Am J Physiol Endocrinol Metab 295: E497–E504, 2008. First published June 17, 2008; doi:10.1152/ajpendo.00045.2008.— Arecoline is one of the major components of betel nuts, which have been consumed as chewing gum in Southeast Asia. In this study, the effects of arecoline on testosterone (T) secretion were explored. Male rats were injected with human chorionic gonadotropin (hCG, 5 IU/kg) or arecoline (1 μg/kg) plus hCG via a jugular catheter. Blood samples were collected at several time intervals subsequent to the challenge. Rat Leydig cells were purified by Percoll density gradient centrifugation and incubated with arecoline, hCG, forskolin, 8-bromo-cAMP (8-Br-cAMP), nifedipine, nimodipine, or tetrandrine at 34°C for 1 h. A single intravenous injection of arecoline resulted in an increase of the hCG-induced level of plasma T. Administration of arecoline (10−8 to 10−6 M) in vitro increased T production in Leydig cells. The stimulatory effect of arecoline on T release in vitro was enhanced by hCG (0.001 IU/ml), forskolin (10−6 M), or 8-Br-cAMP (10−5 M). By contrast, nifedipine, nimodipine, or tetrandrine inhibited the increased T concentrations induced by arecoline. Western blot showed that arecoline increases steroidogenic acute regulatory (StAR) protein expression compared with vehicle. These results suggested that arecoline stimulates testosterone production by acting directly on Leydig cells via mechanisms involving an activation of L-type calcium channels, increasing the activity of 17β-hydroxysteroid dehydrogenase and enhancing the expression of StAR.

Arecoline; Leydig cell; L-type calcium channel; testosterone

Arecoline (1,2,5,6-tetrahydrol-1-methyl-3-pyridinecarboxylic acid methyl ester) (Fig. 1) is an alkaloid extracted from betel nuts (Areca catechu L.). Four major alkaloids are found in betel nut: arecoline (7.5 mg/g wt), arecaidine (1.5 mg/g wt), guvacoline (2.0 mg/g wt), and guvacine (2.9 mg/g wt) (56). Epidemiological studies showed a strong correlation between oral cancer and betel nut-chewing habit (16, 22, 50). Arecoline and/or its alkaloids have been shown to be characterized by carcinogenicity (16, 34, 45), immunotoxicity (42), genotoxicity (30, 46), and teratogenicity (46) in animal model systems. In addition, arecoline has been shown to be mutagenic in mammalian cells, especially in oral mucosal fibroblasts (5, 44). The increased frequency of micronucleated cells, chromosomal aberrations, and sister chromatid exchanges in exfoliated cells of the buccal mucosa was observed in areca-nut consumers (9, 11). In addition, study showed that arecoline enhances the frequency of chromosomal aberrations and micronuclei in mouse bone marrow cells in vivo (12).

Arecoline mimics the actions of acetylcholine and exerts its effects at both muscarinic and nicotinic receptors (3). Studies showed that arecoline readily penetrates the blood-brain barrier (35) and exerts its excitatory action by binding to M2-muscarinic receptors on the cell membrane of neurons of the locus coeruleus (61). Calogero et al. (4) showed that the cholinergic agonist arecoline stimulates the hypothalamic-pituitary-adrenal (HPA) axis in the rat, and this effect is mediated mainly by the release of endogenous corticotropin-releasing hormone (CRH). Arecoline, injected intravenously to catheterized, freely moving male Sprague-Dawley rats stimulated plasma ACTH and corticosterone release in a dose-dependent fashion. Arecoline stimulates the HPA axis via secretion of CRH.

It has been confirmed by the dose-dependent ability of arecoline to cause hypothalamic CRH secretion in vitro and its failure to elicit ACTH and corticosterone secretion by dispersed anterior pituitary and adrenocortical cells in culture (4). Arecoline at concentrations of 0.2–2 μM significantly elevated the number of micronucleated cells in a dose-dependent manner (24). In addition, significant prolongation of cell cycles was observed by treatment with arecoline (~2 μM) in Chinese hamster ovarian cells (24). Moreover, morphology abnormality and unscheduled DNA synthesis were observed in the arecoline-treated germ cells of the mouse (47). Intravenous arecoline administration (3 mg/person) was followed by the increases in plasma epinephrine and ACTH, which were maximal at 10 and 20 min, respectively (32). Although there is no evidence proving that arecoline affects the thyroid function, the speed of induction of rapid eye movement sleep induced by arecoline had a modestly significant negative correlation with free thyroxine (T4) index (20). Panda and Kar (29) showed that a low dose of betel leaf extract was found to increase the triiodothyronine (T3) concentration and T3-to-T4 ratio along with a decrease in T4 concentration. By contrast, increased T4 and decreased T3 and T3-to-T4 ratios were observed in higher-dose betel leaf extract. In Alzheimer’s patients, elevated plasma ACTH and cortisol were observed in acute high-dose but not in low-dose arecoline administration (2). These studies indicated that arecoline might affect the endocrine system. However, it is still unclear whether arecoline affects reproductive function.

To examine the possible physiological effects of arecoline, we studied the acute effects of arecoline on endocrine systems. The purpose of this study was to determine the effect of arecoline on human chorionic gonadotropin (hCG)-stimulated

* S.-W. Wang and P. S. Wang contributed equally to this work.

Address for reprint requests and other correspondence: S.-W. Wang, Dept. of Physiology, School of Medicine, Chang Gung Univ., Kweisan, Taoyuan, 33333, Taiwan, ROC (e-mail: swwang@mail.cgu.edu.tw).

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked "advertisement" in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
testosterone production in rat Leydig cells, and to 2) determine the mechanisms of this effect at the molecular level. In addition, we also investigated the direct effects of arecoline on purified Leydig cells in vitro. The data presented here demonstrate that arecoline stimulates both basal and hCG-evoked testosterone production in rat Leydig cells. The data also indicate that arecoline stimulates the protein expression of StAR protein.

MATERIALS AND METHODS

Animals. Male Sprague-Dawley rats weighing 300–350 g were housed in a temperature-controlled room (22 ± 1 °C) with 14 h of artificial illumination daily (0600–2000) and food and water ad libitum. The use of the animals was approved by the Institutional Animal Care and Use Committee of the National Yang-Ming University. All animals received humane care in compliance with the principles of laboratory animal care and the Guide for Care and Use of Laboratory Animals, published by the National Science Council (Taiwan, Republic of China).

Materials. BSA, HEPES, Hank’s balanced salt solution, Medium 199, sodium bicarbonate, penicillin-G, streptomycin sulfate, heparin, collagenase, arecoline, hCG, forskolin, 8-bromo-cGMP (8-Br-cAMP), and testosterone were purchased from Sigma Chemical (St. Louis, MO). Trilostane (4,5-epoxy-17-hydroxy-3-oxoandrostane-2-carboxitrile), an inhibitor of 3β-hydroxysteroid dehydrogenase (HSD), was provided by Sanofi-Synthelabo (Malvern, PA). Anti-cytokrome P450scc (P450scc) antibody was provided by Dr. Bon-Chu Chung (Academia Sinica, Taipei, Taiwan, ROC), and anti-steroidogenic acute regulatory (StAR) antibody was provided by Dr. D. M. Stocco (Department of Cell Biology and Biochemistry, Texas Tech University Health Sciences Center, Lubbock, TX). [3H]testosterone and [3H]pregnenolone were obtained from Amersham Life Science Limited (Buckinghamshire, UK).

Effect of arecoline on plasma testosterone in rats. Male rats were divided into four groups with seven to eight rats in each group. Each animal was anesthetized with ether and catherized via the right jugular vein (53, 57). After 20 h, they were infused with 1 ml of saline, arecoline (1 μg/kg; Sigma Chemical), hCG (5 IU/kg), or hCG + arecoline via a jugular catheter. Blood samples (0.3 ml each) were collected from the jugular catheter at 0, 30, 60, 120, 180, 240, 300, and 360 min after infusion.

Plasma was separated by centrifugation at 10,000 g for 1 min and stored at −20°C. To measure the concentrations of testosterone, 0.1 ml plasma was mixed with 0.5 ml diethyl ether, agitated for 20 min, centrifuged at 1,000 g for 5 min, and then quick-frozen in a mixture of acetone and dry ice. The organic phase was collected, dried, and reconstituted in a buffer solution containing 0.1% gelatin in PBS (pH 7.5). The concentrations of testosterone in the reconstituted extracts were measured by RIA.

Effect of arecoline on luteinizing hormone release in vitro. Male rats were decapitated, and the anterior pituitary (AP) glands were bisected, preincubated, and then incubated with Locke’s solution in the presence of arecoline (10−7 to 10−6 M) with or without 10 nM gonadotropin-releasing hormone (GnRH) at 37°C for 30 min. At the end of incubation, media were collected for measurement of luteinizing hormone (LH) by RIA.

Preparation of rat Leydig cells. Animals were killed, and the testes were collected and decapsulated. Testicular interstitial cells were isolated with the collagenase dispersion method as previously described (6). The procedure used for preparing Leydig cells has been described elsewhere (15). Testicular interstitial cells were centrifuged at 200 g for 10 min at 4°C. The cell pellet volume was suspended in the incubation medium (1% BSA in medium 199 with 25 mM HEPES, 2.2 g/ml sodium bicarbonate, 100 IU/ml penicillin-G, 50 μg/ml streptomycin sulfate, 2,550 USP K/1 U heparin, pH 7.4, and aerated with 95% O2 and 5% CO2) to 5 ml and then added gently to the upper layer of the continuous Percoll gradient. The continuous Percoll gradient (20 ml/pool) was made by adding 9 parts of Percoll to 11 parts of 1.8 concentrated incubation medium before centrifugation at 20,000 g for 60 min at 4°C. The mixture of testicular cells was loaded on the Percoll gradient and centrifuged at 800 g for 20 min at 4°C. Leydig cells were located in the 3- to 7-ml layer from the bottom. The Leydig cell layer was collected, diluted to 10 ml in incubation medium, and then centrifuged at 200 g for 10 min at room temperature.

After repeating the washing steps, the cell pellet was suspended to 10 ml in incubation medium. The cell concentration (2 × 105 cells/ml) and viability (95%) were determined by using a hemacytometer and the trypan blue method. To measure the abundance of Leydig cells in our preparation, the 3β-HSD staining method was used (4, 24). The cells (2 × 105 cells/ml) were incubated with a solution containing 0.2 mg/ml of nitro blue tetrazolium (Sigma) in 0.05 M PBS, pH 7.4, at 34°C for 90 min. When the blue formazan deposit sites of 3β-HSD activities were developed, the abundance of Leydig cells was determined by using a hemacytometer. Macrophages were determined by flow cytometry with fluorescein isothiocyanate-conjugated monoclonal antibody (ED1, IgG1; Biosource International, Foster City, CA). Our preparation contained ~87% Leydig cells and very few macrophages.

Effects of arecoline on testosterone release by rat Leydig cells. Cells at a concentration of 1 × 106 cells/ml were preincubated at 34°C for 1 h in a controlled atmosphere (95% O2 and 5% CO2) and shaken at 100 cycles/min. The supernatant fluid was decanted after centrifuging the tubes at 100 g for 10 min. The cells were then incubated with arecoline (0, 10−8, 10−7, or 10−6 M) in 200 μl of fresh medium. Following 1 h incubation, 1 ml of ice-cold 0.1% gelatin-PBS, pH 7.5, was added to stop the incubation. The medium was centrifuged at 100 g for 10 min, and the supernatant was stored at −20°C until analyzed for testosterone by RIA.

Aliquots (1 ml) of the cell suspensions (1 × 105 cells/ml) were challenged with arecoline (10−7 M) in the presence of hCG (0.001 IU/ml), forskolin (an adenyl cyclase activator, 10−6 M), or 8-Br-cAMP (a membrane-permeable analog of cAMP, 10−5 M) in 200 μl of fresh medium. At the end of incubation, the media were collected for testosterone RIA.

Effects of arecoline on the functions of 17β-HSD in rat Leydig cells. In this study, Leydig cells were incubated for 1 h with or without arecoline (10−7 M) in the presence of immediate precursors of testosterone, androstenedione (10−7 and 10−5 M). At the end of incubation, the media were collected for testosterone RIA. The level of testosterone was an index of the activity of 17β-HSD in rat Leydig cells.

Effects of arecoline on the activities of calcium channels in rat Leydig cells. Rat Leydig cells were incubated for 1 h with or without arecoline (10−7 M) in the presence of absence of tetrandrine (a blocker for both L-type and T-type calcium channels, 10−5 M), nifedipine (a blocker for L-type calcium channel, 10−5 M), and nimodipine (a blocker for L-type calcium channel, 10−5 M). At the end of incubation, the media were collected for testosterone RIA.

Effects of arecoline on pregnenolone production stimulated with 25-OH-cholesterol (25-OH-C) in rat Leydig cells. Pregnenolone is the product of P450sc by conversion of cholesterol. Intracellular pregnenolone is metabolized by 3β-HSD (Fig. 1). To investigate the production of pregnenolone, we used trilostane (an inhibitor of 3β-HSD) to inhibit the catabolism of pregnenolone. Leydig cells (1 × 105 cells/ml) were preincubated with incubation medium for 1 h at 34°C. Cells were primed with trilostane (10−6 M) for 30 min and then incubated for 1 h with arecoline (10−7 M). At the end of incubation, the media were collected for pregnenolone RIA.

For kinetic analysis of P450sc, Leydig cells (1 × 105 cells/ml) were primed with trilostane (10−5 M) for 30 min and then incubated for 1 h with arecoline (10−7 M) in the presence of 25-OH-C (10−6 to
10^{-4} M). At the end of incubation, the media were collected for pregnenolone RIA.

Hormone RIAs. Testosterone concentrations in media were determined by RIA as described previously (53, 57). The sensitivity of the testosterone RIA was 2 pg/assay tube. The intra-assay and interassay coefficients of variation were 4.1% (n = 6) and 4.7% (n = 10), respectively.

The concentrations of pregnenolone were determined by RIA, as described previously (7). The sensitivity of the pregnenolone RIA was 16 pg/assay tube. The intra-assay and interassay coefficients of variation were 2.3% (n = 6) and 3.7% (n = 4), respectively.

The concentrations of LH were determined by RIA as described previously (7). The sensitivity of the LH RIA was 0.1 ng/assay tube. The intra-assay and interassay coefficients of variation were 2.0% (n = 6) and 4.5% (n = 8), respectively.

Western blot analysis. The Western blotting method has been described elsewhere (6, 25). Leydig cells (1 × 10^6 cells/ml) were incubated with or without arecoline (10^{-7} to 10^{-5} M) for 1 h. At the end of incubation, cells were washed twice with ice-cold saline and then homogenized, and the protein was extracted in 50 μl of homogenization buffer (1.5% sodium lauroylsacrosine, 2.5 mM Tris base, 1 mM EDTA, and 0.1% phenylmethylsulfonyl fluoride, pH 7.8). The cell extract was centrifuged at 12,000 g for 10 min at 4°C. The supernatant was separated, and protein concentration was determined by modifying the Bradford protein assay method (62). SDS-PAGE sample buffer (0.06 M Tris base, 2% SDS, 0.0005% bromphenol blue, 6% sucrose, and 50 μM dithiothreitol) was added to the samples, and, after boiling for 5 min, the samples were stored at −20°C until they were used.

Samples (20 μg) were electrophoresed on a 12% minigel by standard SDS-PAGE procedures, along with prestained molecular weight markers (Bio-Rad, Hercules, CA). Gels were electrophoresed at 75 V for 15 min and then 150 V for 30 min. The protein bands were transferred to polyvinylidene difluoride membranes (NEN Life Sciences Products, Boston, MA) with a semidyry transfer cell (Bio-Rad) for 45 min in a blotting solution. The membrane was washed in 0.8% NaCl, 0.02 M Tris base, and 0.3% Tween 20 (pH 7.6; TBS-T buffer) for 5 min and blocked by a 120-min incubation in blocking buffer (TBS-T buffer containing 5% nonfat dry milk). The membrane was then incubated overnight with anti-StAR (1:1,000), anti-P450scc (1:2,000), and anti-β-actin (1:8,000). After three washes for 5 min each with TBS-T buffer, the membranes were incubated for 2 h with horseradish peroxidase-conjugated secondary antibody (1:6,000). Specific signals were detected by enhanced chemiluminescence (ECL Western blotting detection reagents; Amersham Life Science Limited).

Statistical analysis. All values were given as the means ± SE. The treatment means were tested for homogeneity by one-way ANOVA, and the differences between specific means were tested for significance by Duncan’s multiple-range test or by paired Student’s t-test (48). A difference between two means was considered statistically significant when P < 0.05.

RESULTS

Effect of arecoline on the concentration of plasma testosterone. The basal level of plasma testosterone was 0.4–0.5 ng/ml (Fig. 2, top). A single intravenous injection of arecoline (1 μg/kg) gradually increased (P < 0.01) the concentration of plasma testosterone. A plateau of plasma testosterone concentration (0.9–1.0 ng/ml) was reached 5–6 h following injection of arecoline.

A single intravenous injection of hCG (5 IU/kg) stimulated the concentration of plasma testosterone by 3.7-fold at 60 min following challenge (Fig. 2, bottom). The concentration of plasma testosterone returned to the basal level 4 h following hCG challenge. After administration of arecoline plus hCG (1 h), the secretion of testosterone increased markedly by 7.2-fold compared with the basal level. The peak and postpeak levels of plasma testosterone were significantly higher (P < 0.01) in rats treated with arecoline plus hCG than in hCG-treated animals (Fig. 2, bottom).

Effect of arecoline on LH release in vitro. Incubation of rat AP with 10 nM GnRH increased (3.2-fold, P < 0.01) the concentration (0.9–1.0 ng/ml) was reached 5–6 h following injection of arecoline. A plateau of plasma testosterone concentration (0.9–1.0 ng/ml) was reached 5–6 h following injection of arecoline.

Fig. 2. Effect of arecoline on the basal (top) and human chorionic gonadotropin (hCG)-stimulated (bottom) level of plasma testosterone in male rats. Rats were given a single intravenous injection of vehicle arecoline, hCG, or hCG + s arecoline via a right jugular catheter and bled at different time intervals after injection. The concentration of testosterone was measured by RIA. **P < 0.01 compared with vehicle or hCG group. P < 0.05 (+) and 0.01 (++) compared with time 0 min. Each value represents the mean ± SE.
release of LH in vitro (Fig. 3). Neither basal nor GnRH-stimulated release of LH was significantly altered by the administration of arecoline (10⁻⁷ to 10⁻⁶ M).

**Effect of arecoline on the basal and cAMP-evoked release of testosterone in vitro.** Administration of arecoline at the doses ranging from 10⁻⁸ M to 10⁻⁶ M dose dependently increased the basal release of testosterone by rat Leydig cells (Fig. 4).

Incubation of rat Leydig cells with 8-Br-cAMP (a permeable analog of cAMP, 10⁻⁵ M), forskolin (an adenylyl cyclase activator, 10⁻⁶ M), or hCG (0.001 IU/ml) significantly increased (P < 0.001) the release of testosterone in vitro. Coincubation of arecoline (10⁻⁷ M) increased not only the basal but also the 8-Br-cAMP, forskolin, and hCG-evoked production of testosterone (P < 0.01, Fig. 5).

**Effect of arecoline on the activity of 17β-HSD.** Incubation of rat Leydig cells with 10⁻⁷ and 10⁻⁵ M of androstenedione (the immediate precursor of testosterone) dose dependently increased the production of testosterone (Fig. 6). Administration of 10⁻⁷ M arecoline significantly enhanced the release of testosterone in response to androstenedione (Fig. 6).

**Effect of arecoline on testosterone release in response to calcium channel blockers.** Although the spontaneous release of testosterone was not significantly altered by the administration of tetrandrine (a blocker of L-type and T-type calcium channels, 10⁻⁵ M), nifedipine (an L-type calcium channel blocker, 10⁻⁵ M), or nimodipine (an L-type calcium channel blocker, 10⁻⁵ M), the arecoline-evoked production of testosterone was significantly reduced by all of these calcium channel blockers (P < 0.01, Fig. 7).

**Effect of arecoline on the activity of P450scc.** To examine the activity of P450scc (an enzyme converts cholesterol into pregnenolone), an inhibitor of 3β-HSD (an enzyme converts pregnenolone into progesterone), trilostane, was employed to incubate with rat Leydig cells. Incubation of trilostane (10⁻⁶ M) with Leydig cells significantly increases the production of pregnenolone (P < 0.01, Fig. 8). Administration of 10⁻⁷ M arecoline increased both basal and trilostane-evoked levels of pregnenolone released by rat Leydig cells (P < 0.01; Fig. 8). In addition, increased pregnenolone release from Leydig cells treated with different concentrations of 25-OH-C with trilostane only or trilostane plus arecoline was observed (P < 0.05; Fig. 9).

**Protein expression of StAR and P450scc.** Bands at 54 kDa (P450scc) and 30 kDa (StAR) were detected in rat Leydig cells. The Leydig cells were challenged with 10⁻⁷ and 10⁻⁶ M of androstenedione for 1 h, and then the protein expression of StAR was increased by the addition of arecoline (Fig. 10B). No difference in the protein expression of P450scc was observed after the addition of arecoline (Fig. 10, A and B).

**DISCUSSION**

Betel is a masticatory substance, and betel chewing is a popular oral habit in Southern Taiwan. Numerous studies showed a significant correlation of betel chewing with the incidence of oral cancer or oral submucous fibrosis (16, 17, 31, 36, 43, 51, 58). Arecoline is one of the major ingredients in betel nuts. The other three are arecaidine, guvacoline, and isoguacoline (55, 56). Each chewer in Taiwan consumed on average 14–23 betel quid a day (47), and each betel quid contains 7.5 mg/g of arecoline (55). Although there is no report concerning the plasma arecoline concentration, in vitro study showed that the arecoline cytotoxicity to gingival keratinocytes was observed at concentrations of 0.8–1.2 mM (18). Therefore, chewing betel quids is thought to be a bad habit associated with malignant cancer, especially the oral cancer. Although a number of studies showed betel chewing is strongly related to oral cancer, betel has been used for the treatment of diarrhea, edema, throat inflammations, and tapeworm (51). In this study, we demonstrated that arecoline, with or without hCG, significantly stimulated testosterone secretion both in vivo and in vitro.
Our results reveal a dose-dependent effect of arecoline, one of the major components in betel nuts, on the changes of testosterone concentration in male rats. In addition, the effects of arecoline on the increased testosterone secretion from isolated Leydig cells were due to, at least in part, the increased steroidogenesis. This conclusion is supported by the following observations.

1) Significantly increased plasma testosterone in rats was observed 60 min after arecoline injection.
2) The hCG-induced plasma testosterone could be enhanced by arecoline at 60 min.
3) Arecoline did not alter the GnRH-induced LH secretion in vitro.
4) Calcium channel blocker blunted the stimulatory effect of arecoline on the secretion of testosterone in vitro.
5) An increase of intracellular StAR protein was observed after arecoline treatment.

In this study, arecoline did not alter the LH secretion from the bisected AP gland treated with GnRH. However, the secretion of testosterone from Leydig cells was stimulated significantly by arecoline alone. We note that there has been no study of plasma concentration of arecoline in patients with betel chewing. Also, no investigation has shown the plasma concentration of testosterone in men who chew betel nuts. Recent studies also indicated that arecoline, with or without LH, enhances either the testosterone production in mouse interstitial cells (60) or plasma testosterone concentration in rats (41). Therefore, the stimulatory effect of arecoline on testosterone secretion was LH independent. In addition, we are
the first, as we know, to demonstrate that arecoline stimulates testosterone secretion from isolated Leydig cells. However, it is still unknown at present whether the action of arecoline on Leydig cells is through muscarinic and nicotinic receptors expressed in other cells and tissues (8, 19, 59).

In Leydig cells, testosterone is synthesized by several metabolic steps, collectively known as steroidogenesis. We examined the effects of arecoline on the activities of 17β-HSD in Leydig cells by challenging the cells in vitro with the immediate precursor of testosterone, androstenedione (\(\Delta_4\) substrate of 17β-HSD). Because androstenedione can be converted to testosterone by 17β-HSD, and production of testosterone stimulated by androstenedione was further enhanced in the presence of arecoline (Fig. 6), we suggested that the activity of 17β-HSD was increased by the administration of arecoline.

It is well known that the conversion of cholesterol into pregnenolone is catalyzed by P450scc enzyme (13). In addition, trilostane is an inhibitor of the 3β-HSD enzyme system with no inherent steroidal activity, and it inhibits the production of progesterone and results in an accumulation of pregnenolone, which is a sensitive index for the activity of 3β-HSD (40, 54). In the presence of trilostane, administration of arecoline increases the production of pregnenolone, suggesting that the activity of P450scc was increased by arecoline (Figs. 8 and 9). In addition, the stimulatory effect of arecoline was observed at both lower (10^{-7} M) and higher (10^{-5} M) concentrations of androstenedione (Fig. 6) and other testosterone precursors (data not shown). Also, the accumulation of pregnenolone was observed in the media treated with arecoline. These results indicate that arecoline affects the activities of several enzymes, at least including P450scc and StAR, required for the steroidogenesis.

The biosynthesis of steroid hormones in the testes, in response to the steroidogenic stimuli including hCG, starts with the transfer of cholesterol from the outer to the inner mitochondrial membrane, which is facilitated by StAR (28, 49). Moreover, the P450scc enzyme is located in the inner mitochondrial membrane (13, 27). Subsequent steroid hormones, including progesterone, testosterone, and estrogen, are synthesized in the endoplasmic reticulum. Therefore, inhibition of StAR activity is associated with the transfer of cholesterol and the inhibition of the steroidogenic response. Our results showed that the expression of StAR protein was enhanced by
arecoline, although this protein production might not be responsible for the immediate increase of testosterone release from Leydig cells.

It is well known that the stimulation of LH on the steroidogenesis in gonad cells (e.g., Leydig cells, granulosa cells, or theca cells) is through the binding of specific receptors, activation of adenylate cyclase, formation of cAMP, protein kinase A activation, phospholipid turnover, inositol trisphosphate formation, and the increase of intracellular calcium (1, 14, 26, 37, 39). The increase of cytoplasmic Ca$^{2+}$/H$^+$ pool and to activate Ca$^{2+}$ influx proposed in 1986 (33). However, the Ca$^{2+}$ influx observed in Leydig cells after the exposure to either LH or hCG (52). In addition, a consistently transient, not sustained, rise in Ca$^{2+}$/H$^+$ was observed in Leydig cells treated with thapsigargin and cyclopiazonic acid (CPA), two sarcoendoplasmic reticulum calcium adenosine triphosphatase inhibitors, in Ca$^{2+}$/H$^+$-free medium (39). This rise in Ca$^{2+}$/H$^+$ indicated that thapsigargin and CPA are able to empty the intracellular Ca$^{2+}$/H$^+$ pool and to activate Ca$^{2+}$/H$^+$ influx (39). This is consistent with the capacitative Ca$^{2+}$/H$^+$ entry model or store-operated Ca$^{2+}$/H$^+$ influx proposed in 1986 (33). However, the influx of external Ca$^{2+}$/H$^+$ induced by the emptying of internal stores in Leydig cells could occur through Na$^+$/Ca$^{2+}$-dependent depolarization of the plasma membrane (38), not through voltage-activated Ca$^{2+}$/H$^+$ channels (VACCs), since VACCs are not expressed in rat Leydig cells (52). Although the level in intracellular calcium was not detected in this study, our results showed that the increase of testosterone secretion from rat Leydig cells treated with $10^{-7}$ M arecoline was significantly reduced by administration of L-type calcium channel blockers, nifedipine and nimodipine, and a blocker of L-type and T-type calcium channel, tetrandrine. These data suggested that the activation of L-type calcium channel in rat Leydig cells is involved in the increase of testosterone production stimulated by arecoline.

Our data have demonstrated that arecoline stimulates testosterone production by acting directly on rat Leydig cells. Although further investigations are required to reveal more mechanisms of arecoline actions, the present findings indicate that moderate consumption of betel nuts may be beneficial only for male sexual ability, whereas excess intake has been proven harmful at least from the immunological function and carcinogenesis point of views. Taken together, the results suggest that arecoline stimulates testosterone production by rat Leydig cells via an enhancement of the expression of StAR as well as the functioning of cAMP and the activation of L-type calcium channels.

ACKNOWLEDGMENTS

The anti-P450$_{17-\alpha}$ antibody was kindly provided by Dr. B. C. Chung, Institute of Molecular Biology, Academia Sinica, Taipei, Taiwan, R.O.C. In addition, the anti-StAR antibody was kindly provided by Dr. D. M. Stocco, Department of Cell Biology and Biochemistry, Texas Tech University Health Science Center, Lubbock, TX. The technical assistance provided by Sung-Yun Chen is also greatly appreciated.

GRANTS

This study was supported by Grant NSC 90-2320-B-182-049 from the National Science Council.

REFERENCES


ARECOline ON TESTOSTERONE RELEASE


