Am J Physiol Heart Circ Physiol
281: H1720–H1727, 2001.

Testosterone relaxes coronary arteries by opening the large-conductance, calcium-activated potassium channel

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Received 10 March 2001; accepted in final form 22 June 2001

Deenadayalu, Viju P., Richard E. White, John N. Stallone, Xumei Gao, and Alfredo J. Garcia. Testosterone relaxes coronary arteries by opening the large-conductance, calcium-activated potassium channel. *Am J Physiol Heart Circ Physiol* 281: H1720–H1727, 2001.—Cardiovascular diseases are often considered to be a predominantly male health problem, and it has been suggested that testosterone exerts deleterious effects on cardiovascular function; however, few experimental studies support this suggestion. Moreover, the cellular and molecular mechanism(s) underlying vascular responses to testosterone is unknown. The present study has investigated the acute effects of testosterone on porcine coronary artery smooth muscle at the tissue and cellular levels. Contractile studies demonstrated that testosterone or dihydrotestosterone (a nonaromatizable metabolite) relaxed these arteries by an endothelium-independent mechanism involving potassium efflux. Direct evidence from patch-clamp studies confirmed that testosterone opened K^+ channels in single coronary myocytes, and further analysis identified this protein as the large-conductance, calcium- and voltage-activated potassium (BK_{Ca}) channel. Moreover, inhibiting BK_{Ca} channel activity significantly attenuated testosterone-induced coronary relaxation. These findings indicate that testosterone relaxes porcine coronary arteries predominantly by opening BK_{Ca} channels in coronary myocytes, and this response may be associated with accumulation of cGMP. This novel mechanism may provide a better understanding of testosterone-induced vasorelaxation reported in recent experimental and early clinical studies.

steroid; vascular; ion channel; vasodilation; androgen

THE INCIDENCE OF CARDIOVASCULAR disease is influenced by both gender and age. For example, the risk of developing coronary artery disease or hypertension is much higher in men than in premenopausal women; however, by the age of 65 years a woman is just as likely to suffer cardiovascular dysfunction as a man of similar age (12, 14). Therefore, it has been proposed that gonadal steroids influence cardiovascular physiology and/or pathophysiology. Specifically, it has been proposed that estrogen may protect against the development of cardiovascular diseases; however, the administration of exogenous estrogen in men may actually increase the risk of death from coronary artery disease (1). Testosterone, on the other hand, is often considered to exacerbate the development of cardiovascular diseases; however, clinical and epidemiological studies of the relationship between testosterone and cardiovascular disease are at best controversial. For example, plasma testosterone levels are reported to correlate either positively or negatively with the incidence of coronary artery disease in men (3, 17). In fact, testosterone is associated with higher levels of high-density lipoprotein in men and was correlated negatively with risk factors such as fibrinogen, plasminogen activator inhibitor-1, and insulin (16), suggesting that hypotestosteronemia may be a risk factor for coronary atherosclerotic heart disease in men. In addition, plasma androgen levels are higher in normotensive males than in their hypertensive counterparts (12). Interestingly, potential therapeutic effects of testosterone on angina pectoris were first reported over 50 years ago (10, 21), with more recent electrocardiographic studies demonstrating that testosterone relieves exercise-induced S-T segment depression (11). In light of these studies, it seems premature to conclude that testosterone promotes cardiovascular dysfunction. Instead, a better understanding of the cellular and molecular effects of testosterone on the cardiovascular system is needed before any definitive conclusions can be made regarding the role of testosterone in cardiovascular disease.

Recent in vitro studies revealed that testosterone produces acute (within minutes) endothelium-independent relaxation of rabbit coronary arteries (24). More

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recent studies from our laboratory demonstrated that testosterone-induced relaxation of the rat aorta is gender and androgen receptor independent and involves both endothelium-dependent and -independent mechanisms (4). Endothelium-dependent and endothelium-independent vasodilatory effects of testosterone were also described in canine coronary conductance and resistance arteries in vivo (2). Interestingly, pharmacological evidence from each of these previous studies suggests that testosterone-induced vascular relaxation might involve potassium efflux; however, to our knowledge, no studies have yet investigated potential effects of testosterone on potassium channels directly with the patch-clamp technique nor has an effect of testosterone on porcine coronary arteries been reported. The purpose of the present study was to assess the direct effect of testosterone on porcine coronary arteries and single myocytes from these vessels. Using isometric coronary vascular preparations and single-channel, patch-clamp recordings, we have identified a specific large-conductance, calcium- and voltage-activated potassium (BK_{Ca}) channel as the primary effector mediating testosterone-induced relaxation of porcine coronary arteries.

METHODS

Arterial tension studies. Fresh porcine hearts from castrated males or gilts were obtained from local abattoirs. The left anterior descending (LAD) artery was excised and placed in ice-cold, low-calcium dissociation medium (DM) of the following composition (in mM): 110 NaCl, 5 KCl, 0.16 $CaCl_2$, 2 $MgCl_2$, 10 HEPES, 10 $NaHCO_3$, 0.5 KH_2PO_4, 0.5 NaH_2PO_4, 10 glucose, 0.49 EDTA, and 10 taurine (pH 6.9). The arteries were kept on ice during their transport to the laboratory. Arterial rings (length, 2 to 4 mm) were prepared from the LADs and mounted in organ baths for isometric tension recording using standard methods. The endothelium was removed in some rings by passing a frayed nylon string through the vessel lumen and gently rubbing the intimal surface. The arterial rings were suspended in organ baths containing Krebs-Henseleit bicarbonate (KHB) solution (37°C, gassed with 95% O_2-5% CO_2) of the following composition (in mM): 122 NaCl, 4.7 KCl, 15.5 $NaHCO_3$, 1.8 $CaCl_2$, 1.2 $MgCl_2$, 1.2 KH_2PO_4, and 11 glucose (pH 7.4). Preparations were equilibrated for 90 min at an optimal passive tension of 2.5 g. Fresh KHB solution was added every 20 min.

After equilibration, rings were stabilized by two successive maximal contractions with 80 mM KCl-KHB (NaCl was replaced with KCl to maintain normal osmolality). The tissues were then allowed to relax and reequilibrate for 30–45 min before further experimentation. Rings were then precontracted with $PGF_{2\alpha}$ (10^{-5} M). After a stable contractile tension was attained, testosterone was added to the baths in a cumulative manner to obtain a complete concentration-response relationship for each ring (5–75 μM). In some experiments, potassium channel inhibitors were added to the bath 25–30 min before testosterone. All drug solutions were prepared fresh daily. Vehicle and time-control experiments were also performed to control for potential effects of ethanol on vasorelaxation and to determine the stability of $PGF_{2\alpha}$-induced precontraction. We did not observe differences in vascular reactivity between arteries from female or castrated male pigs.

Isolation of coronary arterial myocytes. Myocytes were isolated from a 3-cm segment of the LAD artery as described previously (22). After the endothelium and adventitia were removed, the tissue was cut into 1-mm strips and placed in the low-calcium DM described above. The strips were then incubated at 37°C in 5 ml of DM containing 5 mg of papain, 4 mM dithiothreitol, and 0.2% bovine serum albumin. After 30 min of gentle shaking, the strips were triturated for 3–5 min, and enzyme activity was terminated by addition of excess enzyme-free cold DM. The solution was then removed and centrifuged at low speed for 6 min. The resultant pellet was resuspended in fresh DM and kept at 4°C.

Patch-clamp studies. Several drops of cell suspension were placed in a recording chamber (Warner Instruments). Single potassium channels were measured in cell-attached patches by filling the patch pipette (2–5 MΩ) with Ringer solution of the following composition (in mM): 140 NaCl, 5 KCl, 1 $MgCl_2$, 2 $CaCl_2$, and 10 HEPES (pH 7.4; 22–25°C). Voltage across the patch was controlled by setting the cellular membrane potential to 0 mV using a high potassium extracellular solution of (in mM) 140 KCl, 10 $MgCl_2$, 0.1 $CaCl_2$, 10 HEPES, and 30 glucose (pH 7.4). After a gigaohm seal on a single myocyte was made, currents were elicited by a series of membrane depolarizations. Currents were filtered at 1 kHz and digitized at 10 kHz. Average channel activity in patches with multiple BK_{Ca} channels was measured as mean open probability times the number of open channels (NP_o), as described previously (22). For consistency, statistics on channel activity were reported at a membrane potential of +40 mV. Although the effect of testosterone was observed at a variety of potentials, BK_{Ca} channels are very clearly identified at +40 mV, thus increasing the accuracy and reliability of NP_o calculations. The number of experiments reported refers to the number of patches studied. In experiments recording potassium channel activity of inside-out patches, the bathing solution exposed to the cytoplasmic surface of the membrane consisted of the following low-calcium solution (in mM): 60 K_2SO_4, 30 KCl, 2 $MgCl_2$, 1 1,2-bis(2-aminophenoxy)ethane-*N,N,N′,N′*-tetraacetic acid, 0.16 $CaCl_2$ (pCa 7), 10 HEPES, 5 ATP, and 10 glucose (pH 7.4; 22–25°C)

Biochemical analysis. cGMP was measured as described previously (23) by using an enzyme immunometric assay kit (Biomol) that included all reagents, antibodies, and microtiter plates. Briefly, endothelium-denuded media strips from coronary arteries were exposed to a single concentration of either 10 μM or 50 μM testosterone or 10 μM sodium nitroprusside (as a positive control) for 30 min with 10 μM 3-isobutyl-1-methylxanthine to inhibit phosphodiesterase activity. Reactions were stopped by adding 0.1 N HCl and boiling for 5 min. The precipitated protein was removed by centrifugation. After colorimetric analysis, nucleotide levels were expressed as femtomoles of nucleotide per milligram tissue weight.

Statistical analysis. Statistical significance between two groups was evaluated by Student's *t*-test for paired data. Comparison among multiple groups were made using a one-way ANOVA test, followed by Tukey's test post hoc to determine significant differences among the means of the data groups. A probability of $P < 0.05$ was accepted as a significant difference. For functional studies, n = number of porcine hearts employed in the study; for patch-clamp studies, n = number of patches studied.

Drugs. 1,2-Bis(2-aminophenoxy)ethane-*N,N,N′,N′*-tetraacetic acid was purchased from Calbiochem. All other agents were purchased from Sigma.

RESULTS

Arterial tension studies. Testosterone produced concentration-dependent relaxation of coronary arterial ring preparations precontracted with $PGF_{2\alpha}$. A complete concentration-response relationship for testosterone-induced relaxation of intact arteries is illustrated in Fig. 1, which reveals that testosterone (75 μM) induces a nearly complete relaxation of 97.4 ± 1% (n = 6). In contrast, precontracted preparations exposed to ethanol (vehicle control) or $PGF_{2\alpha}$ alone (time control) relaxed no more than an average of 11.3 ± 2%. The sensitivity (EC_{50} value) of coronary arterial rings to testosterone-induced relaxation was 26.4 ± 4 μM. The importance of endothelium in mediating testosterone-induced coronary arteries relaxation was investigated by obtaining a series of complete concentration-responses relationships (Fig. 2). In these experiments, removal of the endothelium resulted in a slight but insignificant shift in the testosterone response curve (EC_{50} values: 31.3 ± 4.8 μM, intact arteries; 44.4 ± 9.7 μM, endothelium removed; n = 7; $P > 0.05$). A similar effect was observed when intact arteries were pretreated for 30 min with 250 μM N^{ω}-nitro-L-arginine methyl ester (EC_{50} value, 39.3 ± 3.5 μM; n = 7 arteries), an inhibitor of nitric oxide synthesis. Furthermore, the maximal relaxation response was similar under all conditions tested (~85%, n = 28 arteries). Because these findings are consistent with previous studies indicating that testosterone induces endothelium-independent relaxation of coronary arteries (24), subsequent tension studies employed endothelium-denuded coronary rings to control for potential indirect effects of vasoactive factors released from endothelium.

Because testosterone can be converted into estrogen by cellular aromatase activity and we had previously reported that estrogen relaxes porcine coronary arteries (22), it was possible that the relaxing effect of testosterone on these arteries might be indirectly mediated by conversion to estrogen. Dihydrotestosterone (DHT), a nonaromatizable testosterone metabolite, was employed to test this possibility. DHT (100 μM) induced a 36.9 ± 3.42% (n = 6) relaxation of coronary arteries precontracted with 10 μM $PGF_{2\alpha}$ (Fig. 3) and exhibited a time course similar to that of testosterone-induced relaxation (Fig. 4).

In solutions with 5 mM physiological concentration of extracellular K^+ ($[K^+]_o$), endothelium-denuded arteries precontracted with 10 μM $PGF_{2\alpha}$ relaxed 77.2 ± 4.1% (n = 8 arteries) in response to a single exposure to 25 μM testosterone (Fig. 4*A*). In contrast, this same concentration of testosterone produced an average relaxation of only 5.1 ± 1.4% in the same artery precon-

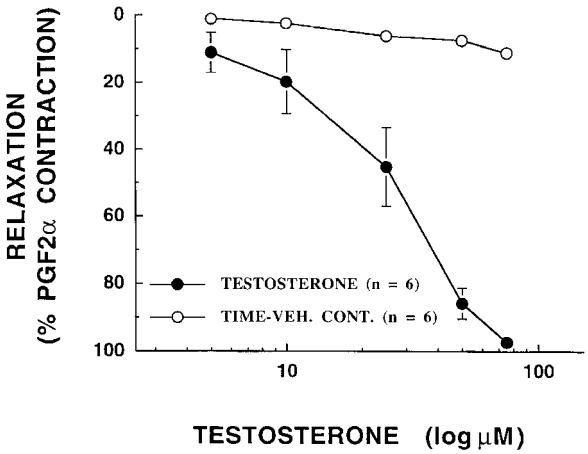

Fig. 1. Testosterone (TES) relaxes porcine coronary arteries. Complete concentration-response relationship for TES-induced relaxation of arterial rings precontracted with 10 μM $PGF_{2\alpha}$ (endothelium intact). Each point represents the mean response ± SE (n, number of responses; error bars for open circles are plotted but are obscured by the symbol). ●, Average relaxation effect produced by cumulative addition of increasing concentrations of TES. ○, Appropriate vehicle controls or time controls in the absence of TES.

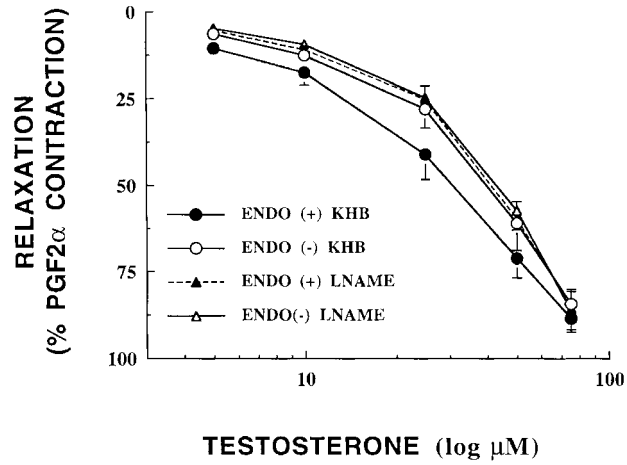

Fig. 2. Effect of endothelium on TES-induced coronary vasorelaxation. Complete concentration-response relationships for TES-induced vasorelaxation of endothelium-intact or -denuded arterial rings, precontracted with 10 μM $PGF_{2\alpha}$ and pretreated with N^{ω}-nitro-L-arginine methyl ester (L-NAME, 250 μM) or Krebs-Henseleit bicarbonate (KHB) buffer. Arterial rings were prepared in quadruplicate from each artery. Each point represents the average response (mean ± SE, n = 7). ENDO (+), endothelium intact; ENDO (−), endothelium denuded.

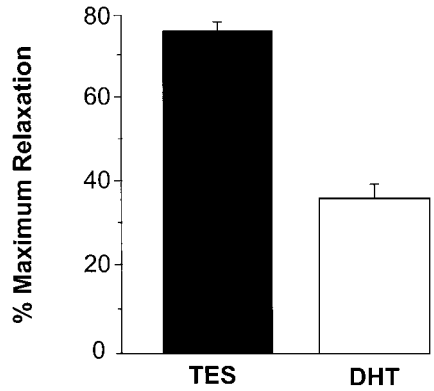

Fig. 3. Androgen-induced coronary relaxation does not require aromatization. Each bar represents the maximal relaxation effect of a single exposure to either 25 μM TES or 100 μM dihydrotestosterone (DHT) on endothelium-denuded coronary rings precontracted with 10 μM $PGF_{2\alpha}$. Solid bar, average relaxing effect of TES alone (n = 6); open bar, average relaxing effect of DHT alone (n = 6).

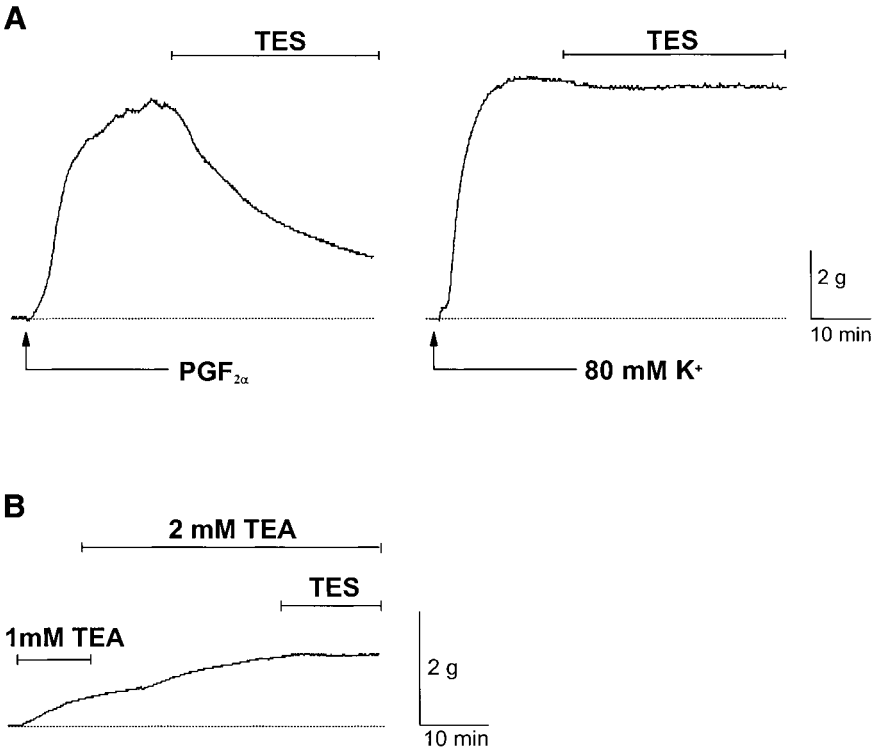

Fig. 4. Testosterone-induced coronary relaxation involves K^+ efflux. *A*: isometric contractile force recordings from the same endothelium-denuded ring precontracted with either 10 μM $PGF_{2\alpha}$ or 80 mM KCl. Exposure of the ring to 25 μM TES is indicated by the timeline above the traces. *B*: blocking K^+ channels with low concentrations of tetraethylammonium (TEA) contracts coronary arteries (n = 6). TES (25 μM) had no significant effect on arteries precontracted with TEA. Exposure of the ring to TEA and/or TES is indicated by the timeline above the traces. Dotted lines, baseline tension.

tracted with 80 mM KCl (n = 6). These findings indicate that the majority (~94%) of testosterone-induced coronary relaxation requires potassium gradients suitable for K^+ efflux and further suggested potential involvement of K^+ channels. Furthermore, pretreating coronary arteries with 1–2 mM tetraethylammonium (TEA) induced a contraction relatively resistant to testosterone (Fig. 4*B*): 25 μM testosterone (with 5 mM $[K^+]_o$) produced only 8.2 ± 1.1% relaxation (n = 6) of TEA-contracted arteries, a response similar to the blunted effect observed in arteries precontracted with 80 mM KCl. At these low concentrations, TEA is a selective inhibitor of BK_{Ca} channels. Moreover, testosterone produced only 12.6 ± 3.3% relaxation (n = 6) in arteries precontracted with $PGF_{2\alpha}$ in the presence of 20 nM iberiotoxin (25 min), a highly selective inhibitor of BK_{Ca} channels (Fig. 5). These studies on intact arteries strongly suggested that testosterone induced coronary relaxation by opening BK_{Ca} channels in coronary smooth muscle; however, direct evidence for ion channel involvement cannot be obtained from studies on intact tissues. To test the hypothesis that testosterone opened K^+ channels, patch-clamp experiments were performed on isolated coronary myocytes to measure the activity of single K^+ channels directly.

Patch-clamp studies. Conclusive evidence for testosterone-induced stimulation of BK_{Ca} channel activity was obtained from patch-clamp experiments on isolated coronary myocytes in which the activity of single K^+ channels was measured directly. Recordings from excised inside-out patches demonstrated that membrane electrical activity was dominated by a single species of high-amplitude channel carrying outward current. Biophysical analysis of single-channel, current-voltage relationships revealed a microscopic conductance of 221 ± 11 pS (n = 3–4 studies) in symmetrical K^+ gradients (140 mM; Fig. 6*A*). In addition, channels were opened by increasing Ca^{2+} concentration at the cytoplasmic surface of inside-out patches (1 μM; NP_o 0.39 ± 0.05; n = 4), whereas 1 mM TEA blocked calcium-stimulated channel activity (NP_o 0.000; Fig. 6*B*; n = 4). These findings identify this protein as the BK_{Ca} channel, which other studies have

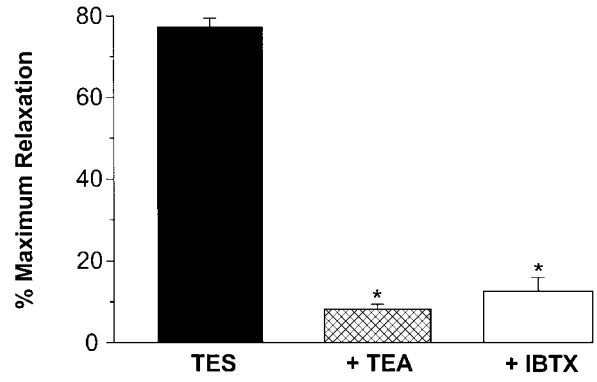

Fig. 5. Testosterone-induced relaxation of coronary arteries involves opening of large-conductance calcium- and voltage-activated potassium (BK_{Ca}) channels. Each bar represents the maximal relaxation effect of a single exposure to 25 μM TES on endothelium-denuded coronary rings precontracted with either 10 μM $PGF_{2\alpha}$ or 1–2 mM TEA. Solid bar, average relaxing effect of TES on rings precontracted with $PGF_{2\alpha}$ (n = 6); crosshatched bar, average relaxing effect of TES on rings precontracted with TEA (n = 6 rings); open bar, average relaxing effect of TES on $PGF_{2\alpha}$-precontracted rings pretreated (25 min) with 20 nM iberiotoxin (IBTX, n = 6). *Significantly lower relaxation response compared with $PGF_{2\alpha}$-precontracted rings exposed to 25 μM TES alone.

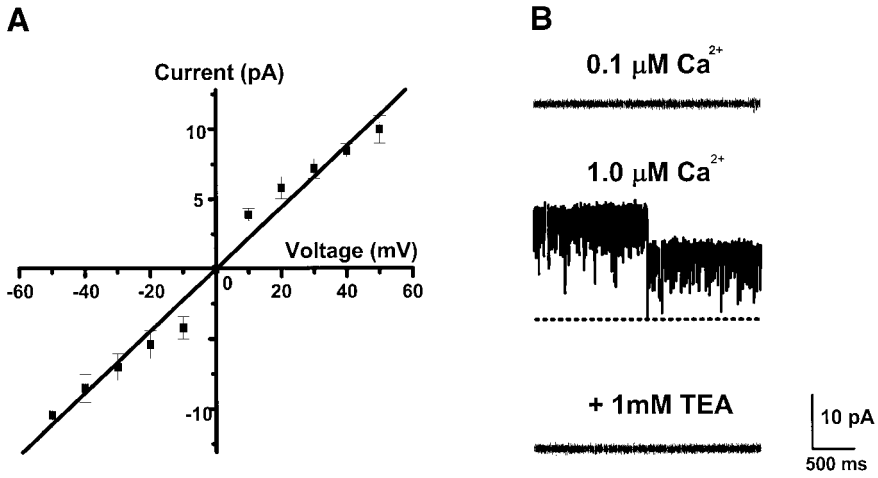

Fig. 6. BK_{Ca} channels are expressed in myocytes from porcine coronary arteries. *A*: current-voltage relationship (means ± SE) for single channel activity in an inside-out patch in symmetrical (140 mM) K^+ (n = 3–4). *B*: increasing intracellular Ca^{2+} concentration stimulates channel activity in another inside-out patch (+40 mV; dashed line indicates closed state). BK_{Ca}-stimulated channel activity was subsequently inhibited by the further addition of 1 mM TEA, a selective blocker of BK_{Ca} channels at this concentration.

demonstrated is the predominant K^+ channel expressed in myocytes from porcine (22) or human (9) coronary arteries.

Recordings from cell-attached patches demonstrated that testosterone opens BK_{Ca} channels in coronary myocytes. Channel openings were infrequent under control conditions (22–25°C) over a range of membrane voltages (0 to +50 mV), as channel NP_o was ~0 (Fig. 7). In contrast, treating cells with 200 nM testosterone (35–40 min) increased channel activity dramatically from an average NP_o of 0.000 ± 0.002 to 0.432 ± 0.04 (+40 mV; n = 6 studies; P = 0.006). The effect of testosterone on BK_{Ca} channel activity was mimicked by 8-bromoguanosine 3′,5′-cyclic monophosphate (8-bromo-cGMP), a cell-permeable cGMP analog (Fig. 8*A*). As noted above, BK_{Ca} channel activity in cell-attached patches is minimal (0.003 ± 0.005) under control conditions, but channel activity increased dramatically (NP_o 0.807 ± 0.08; +40 mV; n = 3 studies) after addition of 500 μM 8-bromo-cGMP (20 min). These studies suggested that cGMP might mediate the effects of testosterone on BK_{Ca} channels in coronary myocytes, and biochemical studies verified that testosterone stimulates cGMP production in these cells. Results from enzymeimmunoassay (Fig. 8*B*) indicated that testosterone stimulates cGMP accumulation in coronary arteries in a concentration-dependent fashion: 10 μM, twofold increase (n = 4 arteries; $P < 0.05$); 50 μM, fourfold increase (n = 4 arteries; $P < 0.05$). As a positive control, 10 μM sodium nitroprusside increased cGMP accumulation sevenfold (n = 4; $P < 0.05$).

DISCUSSION

The present study is the first to report testosterone-induced relaxation of porcine coronary arteries in vitro. DHT, a nonaromatizable testosterone metabolite, also relaxed coronary arteries, suggesting that aromatization to estrogen is not required to produce this relaxation response. Furthermore, this response required physiological gradients of potassium, suggesting potential involvement of potassium channels. Subsequent patch-clamp studies provided direct molecular evidence that testosterone stimulates the activity of BK_{Ca} channels in single coronary myocytes, possibly via cGMP. Moreover, these cellular studies are completely consistent with functional studies of coronary arteries demonstrating that BK_{Ca} channels mediate

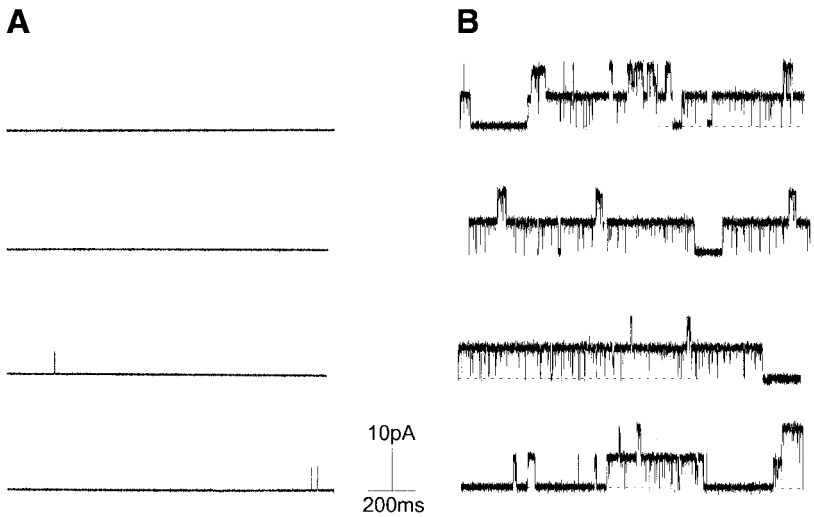

Fig. 7. TES stimulates the activity of single BK_{Ca} channels in myocytes from porcine coronary arteries. Traces are continuous recordings from the same cell-attached patch (+40 mV) before and 40 min after treatment with 200 nM TES. Channel openings are upward deflections from baseline (closed state), which is represented by dashed lines.

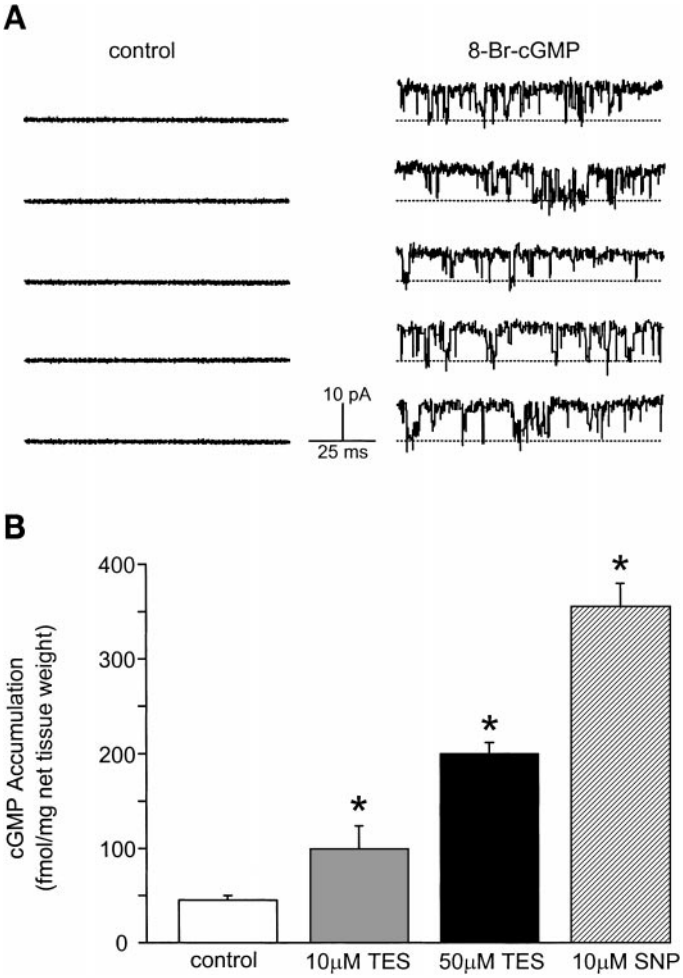

Fig. 8. cGMP opens BK_{Ca} channels in single myocytes from coronary smooth muscle, and cGMP concentration is also increased by TES. *A*: recordings from the same cell-attached patch (+40 mV) before (control) and 20 min after exposure to 500 μM 8-bromo-cGMP (8-Br-cGMP). Channel openings are upward deflections from baseline (closed state), which is represented by dashed lines. *B*: cGMP levels before (control) and 30 min after exposure to either 10 μM TES, 50 μM TES, or 10 μM sodium nitroprusside (SNP; positive control). Data are the cGMP concentrations of 4 separate determinations (means ± SE). *Significant increase in cGMP concentration compared with control levels ($P < 0.05$).

nearly all of testosterone-induced relaxation. Iberiotoxin, a highly specific antagonist of BK_{Ca} channels, attenuated testosterone-induced coronary relaxation by 84% (Fig. 5). Therefore, we propose that stimulation of BK_{Ca} channel activity can account for the majority of testosterone-induced relaxation of porcine coronary arteries.

Recent studies demonstrated that testosterone relaxes rabbit coronary arteries or aorta (24) and rat thoracic aorta (4) in vitro and canine coronary arteries in vivo (2). Both endothelium-dependent and -independent effects of testosterone are reported in these studies. Therefore, testosterone may have multiple sites of action. In the present study on porcine coronary arteries, removal of the endothelium did not affect testosterone-induced coronary relaxation significantly; therefore, it is highly likely that the primary site of testosterone action in porcine coronary arteries is the vascular smooth muscle cell. Regardless of the target, it is clear that testosterone modulates the excitability of vascular smooth muscle, and the present study now provides direct molecular evidence that testosterone opens potassium channels in vascular smooth muscle cells. Furthermore, we have identified the BK_{Ca} channel as the primary effector molecule mediating this potassium efflux and subsequent relaxation of porcine coronary arteries. Myocytes from both human (9) and porcine (19) coronary arteries express BK_{Ca} channels at high density, and because of their large conductance, these channels help set and maintain the resting potential of vascular smooth muscle cells under physiological conditions (20). Moreover, inhibition of BK_{Ca} channels by TEA (Fig. 4*B*) or iberiotoxin (22) induces contraction of porcine coronary arteries in vitro, confirming the importance of these channels in regulating tension under either stimulated or unstimulated conditions. An additional feature of interest regarding these channels is their ability to provide a repolarizing negative-feedback mechanism to reverse active contraction due to increased intracellular levels of calcium. Because single-channel studies clearly demonstrated increased BK_{Ca} channel activity to be the predominant effect of testosterone, we conclude that the BK_{Ca} channel is an important effector of testosterone in these myocytes. Previous in vitro studies reported that glibenclamide, an inhibitor of the ATP-sensitive potassium channel, had no effect on testosterone-induced relaxation of rabbit coronary arteries (24), although a subsequent study reported that this compound reduced the effect of testosterone on smaller resistance coronary vessels in the dog (2). In addition, neither glibenclamide nor 1 mM TEA inhibited testosterone-induced relaxation of the rat aorta, whereas 4-aminopyridine attenuated the response to testosterone by 44% (7). Taken together, these findings suggest that the nature of potassium channel stimulation by testosterone may be heterogeneous with respect to artery and/or species. However, the identity of K^+ channel(s) stimulated in these arteries will remain somewhat speculative until patch-clamp studies are performed on myocytes isolated from each vessel. In contrast, the present study now provides direct evidence that BK_{Ca} channel activity is stimulated by testosterone in porcine coronary arteries. In support of our findings, a recent study by Crews and Khalil (5) has demonstrated that testosterone inhibits $^{45}Ca^{2+}$ influx in porcine coronary arteries but does not affect release of intracellular calcium. These findings are consistent with those of the present study that strongly suggest that testosterone inhibits calcium channel activity by opening BK_{Ca} channels, resulting in hyperpolarization of the vascular cell membranes and closing of the voltage-dependent calcium channels.

Although the present studies have identified an effector molecule (BK_{Ca} channel) that mediates testosterone-induced relaxation of coronary arteries, the complete transduction mechanism involved in this process remains to be elucidated. One signaling molecule

in this process appears to be cGMP, which is increased in coronary smooth muscle after treatment with testosterone (Fig. 8*B*). Furthermore, studies on cell-attached patches verified that cGMP also opened BK_{Ca} channels in single coronary myocytes, thus mimicking the effect of testosterone on these cells. Therefore, evidence from both functional and biochemical studies is consistent with the hypothesis that cGMP mediates the effect of testosterone on porcine coronary arteries. However, the present study cannot exclude involvement of other potential signaling mechanism. Although it is unclear at present how androgens might stimulate production of cGMP in vascular smooth muscle in the absence of endothelium, a similar nongenomic, nucleotide-dependent mechanism of action has been proposed for other gonadal steroids. For example, estrogen also increases cGMP accumulation and stimulates BK_{Ca} channel activity in coronary smooth muscle (6).

Because testosterone and estrogen produce similar effects in coronary smooth muscle cells, it was possible that the stimulatory effects of testosterone were actually indirect, i.e., due to aromatization to estrogen. However, the present study suggests that testosterone-induced relaxation of porcine coronary arteries probably involves a direct effect of the androgen molecule on the vasculature. A nonaromatizable metabolite of testosterone, DHT, produced a similar vasodilatory effect in a similar time frame, albeit with an apparently lower sensitivity. This finding is consistent with previous studies of the rat aorta (8) demonstrating that testosterone-induced relaxation was a structurally-specific effect of the androgen molecule. In that study, maximal relaxation by DHT (69%) was substantially less than that produced by testosterone (100%). Furthermore, previous studies have demonstrated that inhibition of aromatase activity with aminoglutethimide had no effect on testosterone-induced relaxation of rabbit coronary arteries (24). Therefore, the present results are consistent with previous findings obtained in other arteries and suggest a direct vasodilatory effect of testosterone that is not likely to depend on conversion to estrogen or other vasoactive steroids. Although it is possible that testosterone is converted to DHT in the vessel wall, this seems unlikely because in virtually all other nonreproductive target tissues, the biological actions of testosterone do not require conversion to DHT. Furthermore, if conversion of testosterone to DHT occurred to any significant extent, then the vasodilatory efficacy and potency of these two androgens should be the same, but evidence from three other androgen analog studies establishes that this is definitely not the case (8, 13, 24). Previous studies have also established that testosterone-induced vascular relaxation is independent of the classical androgen receptor (4). In fact, testosterone conjugated with bovine serum albumin produced a greater relaxation of the rat aorta compared with unconjugated testosterone (8), implicating involvement of a peripheral cell membrane (nonnuclear) site of action. In addition, previous studies of the rabbit coronary artery reported that an androgen receptor antagonist had no effect on testosterone-induced relaxation (24). If testosterone does indeed activate an androgen receptor in porcine coronary arteries, it seems unlikely that this process would involve the classic genomic pathway, because the relaxation effect of testosterone occurs within minutes, not hours.

Although the present study provides convincing evidence that the BK_{Ca} channel is the effector molecule mediating testosterone-induced relaxation of porcine coronary arteries in vitro, low micromolar concentrations were required to obtain maximal relaxation of isolated tissues. These findings are consistent with previous studies, which also demonstrated that micromolar concentrations of testosterone were required to produce relaxation of intact arteries in vitro (4, 7, 8, 24). In contrast, lower concentrations of testosterone stimulated BK_{Ca} currents in single coronary myocytes. This is consistent with the in vivo studies of Chou et al. (2), which indicated 100 nM testosterone increased coronary blood flow significantly. Once again, however, micromolar concentrations of testosterone were required to produce maximal responses. The apparent greater sensitivity of isolated cells could result from the substantial differences in diffusion distance, tissue equilibration and the resultant cellular concentrations of testosterone that would be expected between single myocytes and the much thicker and histologically more complex structure of the intact vessel wall. The multiple concentric layers of collagen and elastin as well as vascular smooth muscle cells provide diffusion barriers that are absent in preparations of isolated cells, and the present study is the first to demonstrate effects of testosterone on single vascular myocytes. To our knowledge, all studies examining the vasodilatory effects of testosterone employ concentrations of testosterone in excess of the high picomolar-nanomolar levels of free hormone found in the plasma under normal conditions. The traditional view has been that only free steroid hormone is biologically active in target tissues. However, simple diffusion of free hormone cannot completely account for the biological activity of testosterone (18). Moreover, recent findings by Ding and Stallone (8) indicate that protein-bound testosterone is actually more efficacious in producing acute vascular relaxation than unbound testosterone. In addition, there is now increasing evidence that plasma levels of steroid hormones do not necessarily correspond to the actual effective intracellular concentrations and that target tissues can accumulate steroid hormones and sex hormone binding globulins (15). Thus accumulating evidence suggests that testosterone concentrations that exceed the "normal" low nanomolar levels are indeed physiologically relevant. Nonetheless, a direct correlation between in vitro experimental data and in vivo conditions will remain somewhat problematic until there is a better understanding of the actual effective intracellular concentration of steroid hormones in target cells.

In summary, the primary goal of this study was to determine the effects of testosterone on porcine coronary arteries. Testosterone induces endothelium-inde-

pendent relaxation of this vessel, and results from both tissue and single-cell experiments demonstrate that this response primarily involves stimulation of BK_{Ca} channel activity. Understanding the signaling mechanisms that couple testosterone receptor activation to K^+ channel stimulation will provide a better understanding of the cellular processes underlying the vasorelaxant effects of testosterone. Such future studies will further underscore the importance of steroid hormones in regulating cardiovascular function and also in treating and/or preventing diseases of the heart and blood vessels.

We thank Landes Meats and Bob Evans Farms for their kind cooperation.

This work was supported by a State of Ohio Research Challenge Foundation grant (to J. N. Stallone and R. E. White), by National Heart, Lung, and Blood Institute Grants HL-54844 and HL-64779 (to R. E. White) and HL-47432 (to J. N. Stallone), and by American Heart Association Grant 995017N (to R. E. White).

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