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Research Article

The present study was undertaken to examine the cellular interaction between a Na+/K(+)-ATPase inhibitor, ouabain, and arginine vasopressin (AVP) in rat vascular smooth muscle cells (VSMC) in culture. Preincubation with 10(-5) M ouabain for 60 min increased basal cytosolic free Ca2+ [(Ca2+]i) concentration and intracellular 45Ca2+ uptake. Ouabain, however, did not affect basal 45Ca2+ efflux or AVP-stimulated 45Ca2+ efflux. As assessed by cell shape change, preincubation with 10(-5) M ouabain for 60 min also enhanced the sustained cellular contractile effect of a submaximal (10(-8) M AVP, 21.5% vs. 30.5%, P less than 0.01) but not maximal dose of 10(-6) M AVP. Preincubation with 10(-5) M ouabain for 60 min did not change AVP-induced V1-specific surface receptor binding or AVP-induced inositol phosphate production but did however potentiate the mobilization of [Ca2+]i induced by a submaximal (10(-8) M AVP, 301 vs. 385 nM, P less than 0.01) but not a maximal dose of AVP. These effects of ouabain on the mobilization of [Ca2+]i were abolished by incubation in Ca2(+)-free buffer or 5 X 10(-5) M verapamil. Ouabain (10(-5) M) also enhanced the sustained cellular contractile effect of a direct protein kinase C activator, phorbol 12-myristate 13-acetate. The present results therefore indicate that the inhibition of Na+/K(+)-ATPase may enhance the vascular action of AVP, and perhaps other vasoconstrictors, by increasing the AVP-induced […]

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Effect of Inhibition of Na⁺/K⁺-Adenosine Triphosphatase on Vascular Action of Vasopressin

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Abstract

The present study was undertaken to examine the cellular interaction between a Na⁺/K⁺-ATPase inhibitor, ouabain, and arginine vasopressin (AVP) in rat vascular smooth muscle cells (VSMC) in culture. Preincubation with 10^{-5} M ouabain for 60 min increased basal cytosolic free Ca^{2+} ($[Ca^{2+}]_i$) concentration and intracellular $^{45}Ca^{2+}$ uptake. Ouabain, however, did not affect basal $^{45}Ca^{2+}$ efflux or AVP-stimulated $^{45}Ca^{2+}$ efflux. As assessed by cell shape change, preincubation with 10^{-5} M ouabain for 60 min also enhanced the sustained cellular contractile effect of a submaximal (10^{-8} M AVP, 21.5% vs. 30.5%, $P < 0.01$) but not maximal dose of 10^{-6} M AVP. Preincubation with 10^{-5} M ouabain for 60 min did not change AVP-induced V_1-specific surface receptor binding or AVP-induced inositol phosphate production but did however potentiate the mobilization of $[Ca^{2+}]_i$ induced by a submaximal (10^{-8} M AVP, 301 vs. 385 nM, $P < 0.01$) but not a maximal dose of AVP. These effects of ouabain on the mobilization of $[Ca^{2+}]_i$ were abolished by incubation in Ca^{2+}-free buffer or 5×10^{-5} M verapamil. Ouabain (10^{-5} M) also enhanced the sustained cellular contractile effect of a direct protein kinase C activator, phorbol 12-myristate 13-acetate. The present results therefore indicate that the inhibition of Na⁺/K⁺-ATPase may enhance the vascular action of AVP, and perhaps other vasoconstrictors, by increasing the AVP-induced mobilization of $[Ca^{2+}]_i$ and by potentiating the activity of protein kinase C stimulated by AVP through enhancing basal and AVP-stimulated cellular Ca^{2+} uptake. (*J. Clin. Invest.* 1990. 86:1241–1248.) Key words: arginine vasopressin • calcium • Na⁺/K⁺-adenosine triphosphatase • ouabain • vascular smooth muscle cell

Introduction

A current theory on the pathogenesis of arterial hypertension proposes that an increased intracellular Na⁺ concentration in the smooth muscle cells of the arterial wall is an important event in the generation of hypercontractility of the resistance vessels (1, 2). Such an increase in intracellular Na⁺ appears to provoke increased Na^+/Ca^{2+} exchange, leading to the elevation of intracellular Ca^{2+}, which in turn favors smooth muscle cell contraction and increased arterial pressure (1–7). In recent years, circulating digitalis-like substances, with Na⁺/K⁺-ATP-

ase inhibitory activity, have been proposed as principal mediators of increased intracellular Na⁺ concentration in hypertension (1, 2). An increased digitalis-like activity has been detected in hypertensive humans (8–14) as well as in animal models of hypertension (15–19). The Na⁺/K⁺-ATPase inhibitors have been also reported to enhance the action of vasopressor hormones (2, 5, 20, 21). However, in spite of evidence indicating that the Na⁺/K⁺-ATPase inhibitors increase vascular contractility and enhance the action of vasopressor hormones, the intracellular mechanisms whereby Na⁺/K⁺-ATPase inhibition enhances the cellular action of vasopressor hormones is not known (22).

The present study was therefore undertaken to examine the cellular interaction of a Na⁺/K⁺-ATPase inhibitor, ouabain, and a vasopressor hormone, arginine vasopressin (AVP), in rat vascular smooth muscle cells (VSMC)[1] in culture. The effect of ouabain on the cellular action of AVP was studied by using cell shape change as an index of the sustained cellular contractile response. The cellular interactions between ouabain and AVP were investigated by examining the effects of ouabain on (*a*) AVP V_1 receptor binding, (*b*) AVP-induced inositol phosphate production, (*c*) basal and AVP-stimulated intracellular $^{45}Ca^{2+}$ uptake, (*d*) basal and AVP-induced $^{45}Ca^{2+}$ efflux, and (*e*) basal and AVP-mobilized cytosolic free Ca^{2+} ($[Ca^{2+}]_i$). In addition, the effects of the calcium channel blocker, verapamil, and the removal of extracellular Ca^{2+} were also examined to assess the mechanism of the effect of ouabain on the cellular action of AVP. Finally, the effect of ouabain on the sustained cellular contraction produced by the protein kinase C activator, phorbol 12-myristate 13-acetate (PMA) was also examined.

Methods

Cell culture. Rat VSMC were isolated using a modification (23–25) of the technique described by Chamley et al. (26). Briefly, the rat thoracic aortas dissected from 8–10 Sprague-Dawley male rats (250–300 g) were incubated in Eagle's minimum essential medium (MEM) containing 2 mg/ml collagenase (Cooper Biomedical Inc., Malvern, PA) for 60 min at 37°C. After the removal of adventitia and small fragments of the outer membrane, the aortas were minced and incubated in Eagle's MEM containing 2 mg/ml collagenase for 2 h at 37°C. The freshly isolated cells were resuspended in Eagle's MEM containing 1 μM L-glutamine, 100 U/ml penicillin, 100 μg/ml streptomycin, and 10% fetal calf serum, pH 7.4. The cells were plated in 35 × 10-mm culture dishes at a density of 1×10^6 and 2×10^6 cells/ml for the cell contraction studies and the subculture, respectively. The cells were incubated in a humidified atmosphere of 95% air and 5% CO_2 at 37°C. All of the experiments except the cell contraction studies were performed in subcultured cells within the fourth passage. The subculture was performed by trypsin-EDTA (0.25–0.1%) treatment. The identity

1. *Abbreviations used in this paper:* IP₂, inositol bisphosphate; IP₃, inositol trisphosphate; PSS, physiological saline solution; VSMC, vascular smooth muscle cells.

of cells was confirmed by electron microscopy and viability was > 95%, as judged by Trypan blue exclusion.

Cell contraction studies. The sustained cellular contractile response was assessed by quantitation of cell surface area changes using phase-contrast microscopy (model IM, Carl Zeiss, Oberkochen, FRG) and a digital imaging analysis system (Zidas, Carl Zeiss). This morphometric analysis is similar to the method reported from our and other laboratories (23, 25, 27). The cell contraction studies were performed 6–8 d after seeding the primary cultures. The magnitude of the shape change response was determined by comparing groups of 14–20 cells. The measurements of cell surface areas were obtained in triplicate and the mean value of one cell was used for comparison. The cells were washed twice with 2 ml physiological saline solution (PSS) (140 mM NaCl, 4.6 mM KCl, 1 mM $MgCl_2$, 2 mM $CaCl_2$, 10 mM glucose, and 10 mM Hepes, pH 7.4) before the first measurement of cell surface area. The cells were incubated with 2 ml of PSS or 10^{-5} M ouabain (Sigma Chemical Co., St. Louis, MO) for 60 min at 37°C and the second measurement of cell surface area was performed. The third measurement of cell surface area was done after 20 min incubation at 37°C with 2 ml PSS or 10^{-5} M ouabain in the absence or presence of effectors; specifically, AVP or PMA (Sigma Chemical Co.) to examine the effects of ouabain on the AVP- or PMA-induced sustained cellular contractile response. The cells with more than a 10% decrease in cell surface area between the first and the second measurement or between the second and the third measurement were considered the contractile cells. The results are expressed as a percentage of the contractile cells.

AVP V_1 receptor binding study. Confluent cell monolayers grown on 35 × 10-mm plastic dishes were used to examine the effect of ouabain on AVP V_1 receptor binding. After the cells were washed twice with 2 ml of PSS, the cells were incubated with 2 ml of PSS or 10^{-5} M ouabain for 60 min at 37°C. At the end of the incubation period the cells were washed twice with 2 ml of ice-cold PSS or 10^{-5} M ouabain and then incubated with 2 ml of ice-cold PSS or 10^{-5} M ouabain containing 2×10^{-9} M[^{3}H]AVP (specific activity, 67.7 Ci/mmol, New England Nuclear, Boston, MA) in the absence or presence of 1×10^{-6} M AVP at 4°C for 60 min. After the incubation the cells were rinsed four times with 2 ml of ice-cold PSS and dissolved with 2 ml of sodium dodecyl sulfate (SDS)-alkaline solution (0.1% SDS and 0.1 N NaOH). Samples (100 μl) were stored at 4°C for protein assay by the method of Lowry et al. (28) and the radioactivity of SDS-alkaline solution was counted using a liquid scintillation counter (Tri-Carb 460C, Packard Instrument Co., Inc., Downers Grove, IL).

Measurement of inositol phosphates. Confluent monolayers on 35 × 10-mm plastic dishes were also used in this study. The measurement of the intracellular levels of inositol phosphates was performed as described (24, 25). The cells were washed twice with 2 ml of inositol-free Dulbecco's modified Eagle's MEM (DME) (Hazleton Research Products Inc., Lenexa, KS) and incubated for 2 d with 1.5 ml of inositol-free DME containing 5 μCi/ml myo-2 [^{3}H]inositol (specific activity, 19 Ci/mmol, Amersham Corp., Arlington Heights, IL) in a humidified atmosphere of 95% air and 5% CO_2 at 37°C. At the time of the experiment, the cells were washed twice with 2 ml of PSS and then incubated with 1 ml of PSS or 10^{-5} M ouabain for 60 min at 37°C. At the end of the incubation the cells were exposed for 10 s at 37°C to 1 ml of PSS or 10^{-5} M ouabain in the absence or presence of 10^{-8} or 10^{-6} M AVP. The reaction was stopped by the addition of 100 μl of ice-cold 100% trichloroacetic acid and the cells were scraped using an Eppendorf pipette tip. The suspensions containing the disrupted cells were centrifuged using a microcentrifuge (model 5413, Eppendorf, Brinkmann Instruments Co., Westbury, NY). The supernatants were washed four times with 3 ml of ether and the water-soluble fractions were brought to pH 7.0 using 1 M Tris-base and stored at −20°C until analysis. The pellets were dissolved with 1 ml SDS-alkaline solution and stored at 4°C for protein assay. The water-soluble fractions were applied to columns containing 1 ml of Dowex (1-x8, formate form) and serially eluted with 2-ml aliquots of H_2O, Borax (5 mM disodium tetraborate [Sigma Chemical Co.], 60 mM sodium formate [Sigma Chemical

Co.]), 0.2, 0.4, and 1.0 M ammonium formate (Sigma Chemical Co.) in 0.1 M formic acid, separating inositol, glycero-phosphatidylinositol, inositol-1-phosphate, inositol bisphosphate (IP_2), and inositol trisphosphate (IP_3), respectively. IP_3 fraction includes 1,3,4- and 1,4,5-IP_3 and 1,3,4,5-inositol phosphate. Samples were collected in scintillation counter vials and counted using a liquid scintillation counter. The extraction procedure has been previously validated in this laboratory with radioactive phosphoinositides.

Intracellular $^{45}Ca^{2+}$ uptake. Confluent monolayers of cells on 60 × 15-mm plastic culture dishes were used to measure intracellular $^{45}Ca^{2+}$ uptake. The cells were washed twice with 2 ml of PSS and then incubated with 2 ml of PSS or 10^{-5} M ouabain containing 2 μCi/ml $^{45}Ca^{2+}$ (specific activity, 12.3 mCi/mg Ca^{2+}; ICN Radiochemicals, Irvine, CA) at 37°C for different times (1, 5, 10, 15, 30, and 60 min). After the incubation period, external $^{45}Ca^{2+}$ was removed by rinsing the dish three times with 5 ml of ice-cold Ca^{2+}-free PSS containing 1 mM EGTA. The cells were treated with hypotonic shock by the addition of 1 ml of deionized water and the disrupted cells were collected using a rubber policeman. The suspension containing the disrupted cells was placed into a microcentrifuge tube with 0.25 ml 4 N perchloric acid and centrifuged using a microcentrifuge (model 5413, Eppendorf). The radioactivity of supernatants and the protein of pellets were measured using the same methods as previously described.

$^{45}Ca^{2+}$ efflux study. Confluent monolayers of cells on 35 × 10-mm plastic dishes were used in this study. The cells were washed twice with 2 ml of PSS and preincubated for 60 min at 37°C with 2 ml of PSS or 10^{-5} M ouabain containing 8 μCi/ml $^{45}Ca^{2+}$ (ICN Radiochemicals). At the end of the preincubation the cells were rapidly washed 10 times during 60 s with 2 ml of PSS or 10^{-5} M ouabain. The medium was removed and replaced with 2 ml of PSS or 10^{-5} M ouabain at each minute from 1 to 6 min. AVP was added at 7 min of the time course of $^{45}Ca^{2+}$ efflux and 1-min samples collected for an additional 5 min. The amount of $^{45}Ca^{2+}$ lost from the cells in each time interval was measured by a liquid scintillation counter. The cells were dissolved for the measurement of intracellular radioactivity and the protein content.

Measurement of $[Ca^{2+}]_i$ concentration. Confluent monolayers of cells were grown on round glass coverslips (13 mm diam) (Fisher Scientific Co., Pittsburgh, PA) for the measurement of $[Ca^{2+}]_i$. The fluorescence indicator dye, fura2/AM (Molecular Probes, Inc., Eugene, OR), was used. After the cells were washed twice with PSS, the cells were incubated with PSS or 10^{-5} M ouabain containing 4 μM fura2/AM at 37°C in a humidified atmosphere of 95% air and 5% CO_2 for 60 min. At the end of the loading period the cells were washed twice with PSS or 10^{-5} M ouabain and inserted into quartz cuvettes (Fisher Scientific Co.) with 3 ml of PSS or 10^{-5} M ouabain. AVP was added to the cells after the measurement of basal $[Ca^{2+}]_i$ concentration. The fluorescent intensity of fura2-loaded cells was measured using a fluorescence spectrophotometer (model 650-10S, Perkin-Elmer Corp., Norwalk, CN) equipped with a thermostatically controlled cuvette holder. The complete intracellular hydrolysis of fura2/AM to fura2 was judged by changes in the excitation and emission spectra. The fluorescence of fura2 was measured using two excitation wavelengths, 345 and 380 nm (5-nm slit), and a 500 nm (5-nm slit) emission wavelength. The ratios of the emitted fluorescence signals at two excitation wavelengths permitted the calculation of $[Ca^{2+}]_i$ concentration independent of cell number, dye loading conditions and dye bleaching. The autofluorescence was measured in similar cells which had not been loaded with fura2/AM and was below 10% of the total fluorescence of fura2 loaded cells. After the subtraction of autofluorescence for each wavelength the $[Ca^{2+}]_i$ concentration was calculated using the method of Grynkiewicz et al. (29). R_{max} and R_{min} were determined by treating the cells with 5×10^{-5} M digitonin and 1×10^{-2} M EGTA, respectively. Since there exists a linear correlation between the maximal change in $[Ca^{2+}]_i$ concentration and the area under the response curve from 0 to 180 s after the addition of the hormonal mediators, maximal changes in $[Ca^{2+}]_i$ were used for the comparison.

Statistical analysis. All results were expressed as the mean±SEM.

The unpaired Student's t test was used for statistical comparison. A P value of less than 0.05 was considered significant.

Results

Effect of ouabain on basal $[Ca^{2+}]_i$ concentration. Since the intracellular Ca^{2+} is thought to be a major determinant of the cellular contractile response to vasopressor hormones, the effect of ouabain on basal $[Ca^{2+}]_i$ concentration was examined to determine the optimal concentration of ouabain for studying the cellular interaction between ouabain and AVP. The incubation of the cells with the different concentrations of ouabain at 37°C for 60 min increased basal $[Ca^{2+}]_i$ concentration in a dose-dependent manner (Fig. 1). Ouabain (more than 10^{-4} M) increased basal $[Ca^{2+}]_i$ concentration beyond 300 nM, which was higher than the maximal $[Ca^{2+}]_i$ response to 10^{-8} M AVP (see Fig. 6 *a*). Therefore in the following studies, 10^{-5} M ouabain was used to examine the cellular interaction between ouabain and AVP.

Effect of ouabain on $^{45}Ca^{2+}$ uptake and efflux. Intracellular $^{45}Ca^{2+}$ uptake and $^{45}Ca^{2+}$ efflux were measured to examine the mechanisms whereby 10^{-5} M ouabain increases intracellular Ca^{2+} concentration. In Fig. 2 is shown the time course of the effect of 10^{-5} M ouabain on intracellular $^{45}Ca^{2+}$ uptake. Ouabain (10^{-5} M) significantly increased intracellular $^{45}Ca^{2+}$ uptake beginning 15 min after its addition as compared with that of vehicle. On the other hand, the preincubation of the cells with 10^{-5} M ouabain at 37°C for 60 min did not effect the basal- or AVP-stimulated $^{45}Ca^{2+}$ efflux (Table I). These results
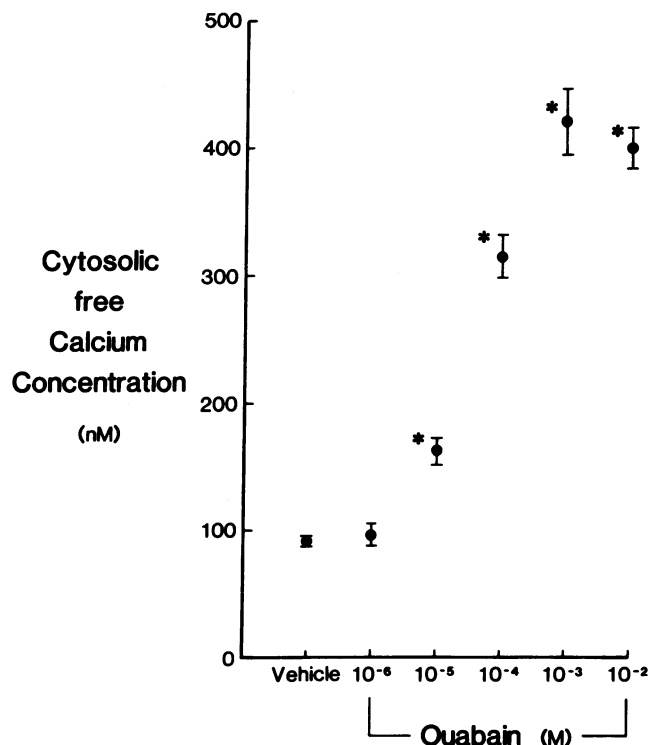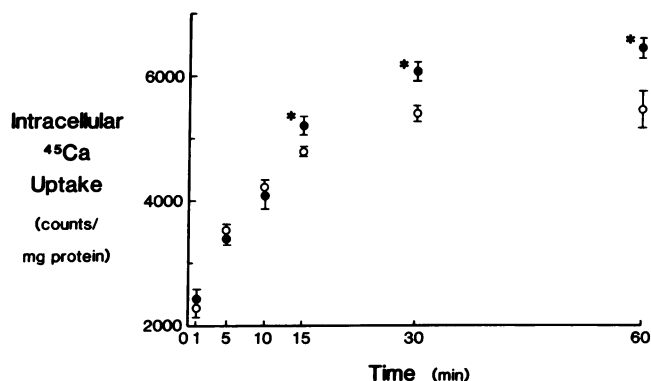

Figure 2. Time course of effect of ouabain on intracellular $^{45}Ca^{2+}$ uptake in rat VSMC in culture. (o) Vehicle and (●) 10^{-5} M ouabain. Values are expressed as mean±SEM ($n = 5$). *$P < 0.01$ (vs. vehicle).

suggest that 10^{-5} M ouabain increased intracellular Ca^{2+} concentration by enhancing cellular Ca^{2+} uptake.

Effect of ouabain on AVP-induced VSMC contraction. The effect of ouabain on the cellular action of AVP was studied by using cell shape change as an index of the sustained cellular contractile response. The incubation of the cells with 10^{-5} M ouabain at 37°C for 60 min did not affect the cell contraction as compared with the vehicle. However, preincubation with 10^{-5} M ouabain for 60 min potentiated the AVP-induced sustained cellular contractile response (Fig. 3). AVP induced a sustained (20 min) cellular contractile response in a dose-dependent manner and the maximal cellular contractile response occurred in 10^{-6} M AVP. The potentiating effect of ouabain was evident with submaximal but not maximal doses of AVP. This effect of ouabain was completely blocked by 5×10^{-5} M verapamil (Fig. 4).

Effect of ouabain on AVP V_1 receptor binding. Scatchard analysis, obtained by the incubation of the cells with 2×10^{-9} M[^{3}H]AVP for 60 min at 4°C, revealed a single class of surface binding sites with a K_d of 4.7×10^{-9} mol and B_{max} of 1.7×10^{-10} mol (30). The preincubation of the cells with 10^{-5} M ouabain at 37°C for 60 min did not change AVP V_1-specific surface receptor binding (100.0 ± 2.3 vs. $95.7\pm0.8\%$, $n = 3$, NS).

Effect of ouabain on AVP-induced inositol phosphate production. The preincubation of the cells with 10^{-5} M ouabain at 37°C for 60 min did not affect submaximal (10^{-8} M) or maximal (10^{-6} M) AVP-induced IP$_2$ and IP$_3$ production (Fig. 5).

Effect of ouabain on basal and AVP-mobilized $[Ca^{2+}]_i$. AVP mobilized $[Ca^{2+}]_i$ from the intracellular Ca^{2+} stores in a dose- and time-dependent manner (Figs. 6, *a* and *b*). The preincubation of the cells with 10^{-5} M ouabain at 37°C for 60 min significantly increased basal $[Ca^{2+}]_i$ and the mobilization of $[Ca^{2+}]_i$ in response to the submaximal dose of AVP (10^{-8} M) (Fig. 6 *a*). The $[Ca^{2+}]_i$ level 2 min after the addition of 10^{-8} M AVP was also significantly higher in the ouabain-treated cells than that in the vehicle (Fig. 6 *a*). However, 10^{-5} M ouabain did not enhance the effect of 10^{-6} M AVP to mobilize $[Ca^{2+}]_i$ (Fig. 6 *b*). The enhancing effect of ouabain on the AVP (10^{-8} M)-induced mobilization of $[Ca^{2+}]_i$ was mainly dependent on an increase in cellular Ca^{2+} uptake in response to AVP. Since incubation in Ca^{2+} free media decreased the AVP-induced mobilization of $[Ca^{2+}]_i$ and also abolished the potentiating ef-

Figure 1. Dose-dependent effect of ouabain on basal cytosolic free Ca^{2+} ($[Ca^{2+}]_i$) concentration in rat VSMC in culture. The cells were incubated with different concentrations of ouabain for 60 min. Values are expressed as mean±SEM ($n = 6$). *$P < 0.01$ (vs. vehicle).

Table I. Absence of Effect of Ouabain on Basal and AVP-induced $^{45}Ca^{2+}$ Efflux in Rat VSMC in Culture

Time (min)	Basal			AVP (10^{-8} M)			AVP (10^{-6} M)		
	1	2	3	1	2	3	1	2	3
Vehicle (cpm/mg protein)	1,099±52	1,029±40	988±58	4,393±371	6,059±354	2,830±140	8,658±88	5,448±144	2,353±205
Ouabain (10^{-5} M) (cpm/mg protein)	1,162±31	1,068±30	996±53	4,919±382	6,144±355	3,072±236	8,821±223	5,596±225	2,361±124

Values are expressed as mean±SEM ($n = 4$). Time shows the time after the addition of effectors. There was no statistical difference between the vehicle and ouabain experiments (10^{-5} M) during the basal or AVP (10^{-8} or 10^{-6} M) periods.

fect of ouabain on the AVP-mobilized [Ca^{2+}]$_i$ without any changes in the effect of ouabain on basal [Ca^{2+}]$_i$ (Table II). The effects of ouabain on basal [Ca^{2+}]$_i$ concentration and the AVP-induced mobilization of [Ca^{2+}]$_i$ were also blocked by 5 × 10^{-5} M verapamil. As shown in Fig. 7, the incubation of the cells with 5 × 10^{-5} M verapamil at 37°C for 60 min induced a significant decrease of basal [Ca^{2+}]$_i$ concentration and the maximal change in the 10^{-8} M AVP-induced mobilization of [Ca^{2+}]$_i$ as compared with the vehicle. In addition, the preincubation of the cells with 5 × 10^{-5} M verapamil completely abolished the potentiating effects of ouabain on basal [Ca^{2+}]$_i$ concentration and the maximal change in [Ca^{2+}]$_i$ in response to 10^{-8} M AVP (Fig. 7).

Effect of ouabain on PMA-induced VSMC contraction. In Fig. 8 is shown the potentiating effect of ouabain on the PMA-induced sustained cellular contractile response. PMA has been shown previously to induce a sustained cellular con-

tractile response in a dose- and time-dependent manner without a rise in [Ca^{2+}]$_i$ (31). In the present study, the preincubation of the cells with 10^{-5} M ouabain at 37°C for 60 min significantly potentiated the submaximal PMA-induced contractile response but did not alter the response to a maximal dose of PMA.

Discussion

Inhibition of Na$^+$/K$^+$-ATPase in vascular smooth muscle is proposed to be associated with an increase in cellular Na$^+$ concentration, enhanced Na$^+$/Ca^{2+} exchange and a rise in cellular Ca^{2+} concentration (1–7). A rise in [Ca^{2+}]$_i$ concentration then may directly increase vascular smooth muscle tone and/ or enhance the effect of circulating vasopressor hormones (2, 5, 20, 21). The present study was undertaken to examine the mechanisms whereby an increase in cellular Ca^{2+} concentration due to the inhibition of Na$^+$/K$^+$-ATPase results in increased contractility of vascular smooth muscle in response to AVP.

It was first necessary to establish the optimal concentration of ouabain suitable for examination of the cellular interaction between ouabain and AVP in cultured rat VSMC. Since preincubation of VSMC with > 10^{-4} M ouabain for 60 min at 37°C increased basal [Ca^{2+}]$_i$ concentration to a level higher than that induced by 10^{-8} M AVP, 10^{-5} M ouabain was used

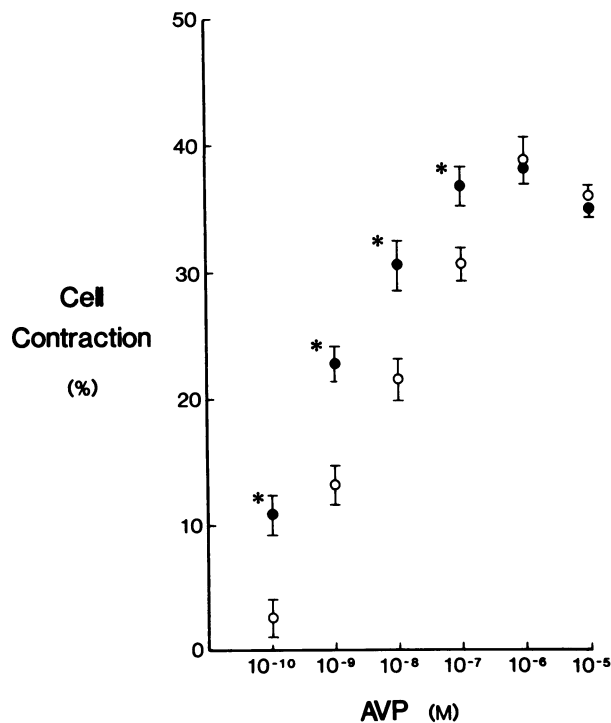Figure 3. Potentiating effect of ouabain on AVP-induced sustained cellular contractile response in rat VSMC in culture. (o) Vehicle and (●) 10^{-5} M ouabain. Values are expressed as mean±SEM ($n = 6$). *P < 0.01 (vs. vehicle).
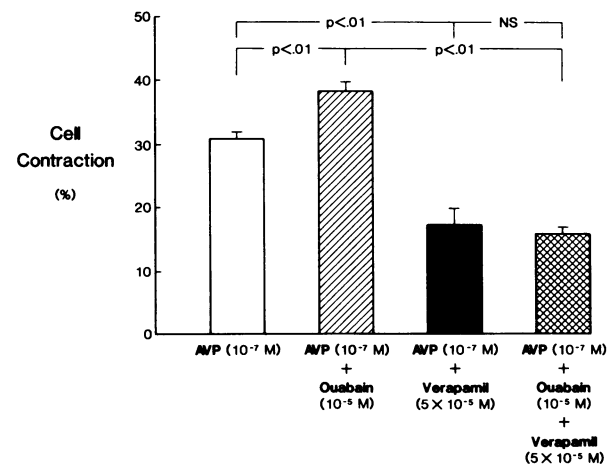

Figure 4. Inhibitory effect of verapamil on potentiation of ouabain in AVP-induced sustained cellular contractile response in rat VSMC in culture. Values are expressed as mean±SEM ($n = 6$).
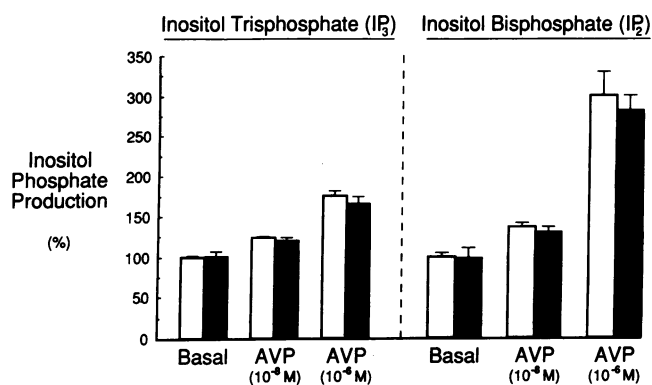
Figure 5. Effect of ouabain on AVP-induced production of inositol phosphates in rat VSMC in culture. Vehicle (*open bars*) and 10^{-5} M ouabain (*solid bars*). Values are expressed as mean±SEM ($n = 5$).

in the present studies. In other tissues and VSMC a similar rise in $[Ca^{2+}]_i$ with inhibition of Na^+/K^+-ATPase has been suggested to be due to an increase in cellular Ca^{2+} uptake (3–8). This interpretation is compatible with the findings in the present studies of a time-dependent enhancement in intracellular $^{45}Ca^{2+}$ uptake and no change in basal $^{45}Ca^{2+}$ efflux in VSMC preincubated with 10^{-5} M ouabain for 60 min at 37°C. Moreover, either the calcium channel blocker, verapamil, or removal of extracellular Ca^{2+} abolished the increase in $[Ca^{2+}]_i$ induced by ouabain.

The present results also demonstrated that preincubation of VSMC with 10^{-5} M ouabain enhanced the effect of submaximal, but not maximal, doses of AVP to induce the sustained cellular contractile response. This effect of ouabain was also completely blocked by verapamil. Taken together, these results implicate increased cellular Ca^{2+} uptake as a factor in the effect of ouabain to enhance AVP-induced vascular smooth muscle contraction.

Previous studies have shown that after AVP binding to the V_1 receptor, AVP activates phospholipase C to produce (*a*) IP_3, which mobilizes $[Ca^{2+}]_i$ from intracellular Ca^{2+} stores to induce the initial cellular contractile response (24, 25, 32–36), and (*b*) diacylglycerol (DAG), (37) which activates protein kinase C (38) to produce the sustained cellular contractile response (31, 39, 40). The cellular interaction between ouabain and AVP was therefore studied by examining the effects of ouabain on AVP V_1 receptor binding, IP_3 production, and
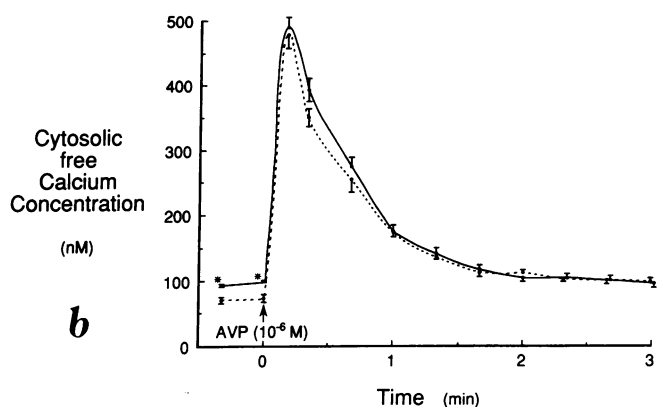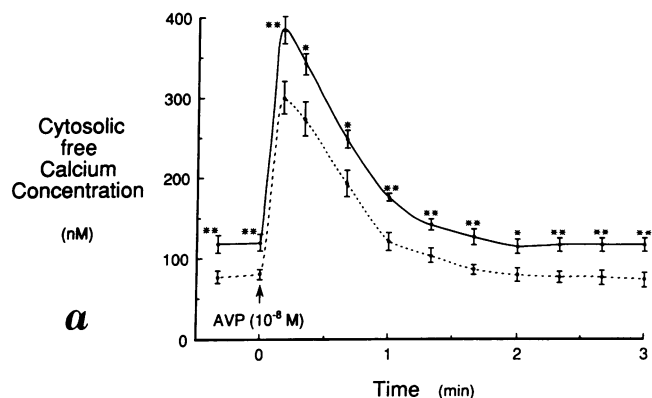

Figure 6. (*a*) Potentiating effect of ouabain on mobilization of $[Ca^{2+}]_i$ in response to submaximal dose of AVP in rat VSMC in culture. AVP (10^{-8} M) was added at 0 min. (○) Vehicle and (●) 10^{-5} M ouabain. Values are expressed as mean±SEM ($n = 5$). *$P < 0.05$, **$P < 0.01$ (vs. vehicle). (*b*) Effect of ouabain on mobilization of $[Ca^{2+}]_i$ in response to maximal dose of AVP in rat VSMC in culture. AVP (10^{-6} M) was added at 0 min. (○) Vehicle and (●) 10^{-5} M ouabain. Values are expressed as mean±SEM ($n = 5$). *$P < 0.01$ (vs. vehicle).

mobilization of $[Ca^{2+}]_i$. The effect of ouabain on the contractile response to the protein kinase C activator, PMA, was also examined to investigate the possible role of a protein kinase C–mediated mechanism in the effect of ouabain on the cellular action of AVP.

Since AVP V_1 receptor binding and AVP-stimulated IP_3 production were not affected by the preincubation with oua-

Table II. Effect of $[Ca^{2+}]_e$ Concentration on an Increase in Basal $[Ca^{2+}]_i$ Concentration and Maximal Change in AVP-induced Mobilization of $[Ca^{2+}]_i$ Due to Ouabain in Rat VSMC in Culture

$[Ca^{2+}]_e$	Basal $[Ca^{2+}]_i$ concentration			Maximal changes in 10^{-8} M AVP-induced mobilization of $[Ca^{2+}]_i$		
	Vehicle	10^{-5} M ouabain	P value	Vehicle	10^{-5} M ouabain	P value
	nM			*nM*		
2 mM	94.0±7.4	169.7±18.9	<0.01	326.0±13.4	459.3±18.1	<0.01
0 mM	35.5±2.1	45.9±5.5	NS	140.6±21.1	135.4±25.4	NS
P value	<0.01	<0.01		<0.01	<0.01	

Values are expressed as mean±SEM ($n = 6$). Abbreviation: $[Ca^{2+}]_e$, extracellular Ca^{2+} concentration.
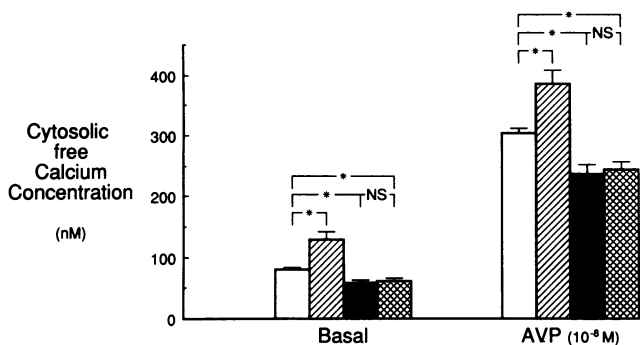
Figure 7. Inhibitory effect of verapamil on potentiation of ouabain in basal $[Ca^{2+}]_i$ concentration and mobilization of $[Ca^{2+}]_i$ in response to AVP in rat VSMC in culture. The results represent the maximal changes in $[Ca^{2+}]_i$, the vehicle (*open bars*), 10^{-5} M ouabain (*hatched bars*), 5×10^{-5} M verapamil (*solid bars*), and 10^{-5} M ouabain and 5×10^{-5} M verapamil (*cross-hatched bars*). Values are expressed as mean±SEM ($n = 6$).

bain, direct effects on receptor activation and transmembrane signal transduction did not seem to be involved in the cellular interaction between ouabain and AVP. The preincubation with 10^{-5} M ouabain did, however, enhance the effect of a submaximal, but not maximal, dose of AVP (10^{-8} M) to increase $[Ca^{2+}]_i$. These findings indicate that the ouabain enhancement of AVP-induced vascular smooth muscle contraction is associated with increased $[Ca^{2+}]_i$ in the absence of alterations in either V_1 receptor binding or phospholipase C
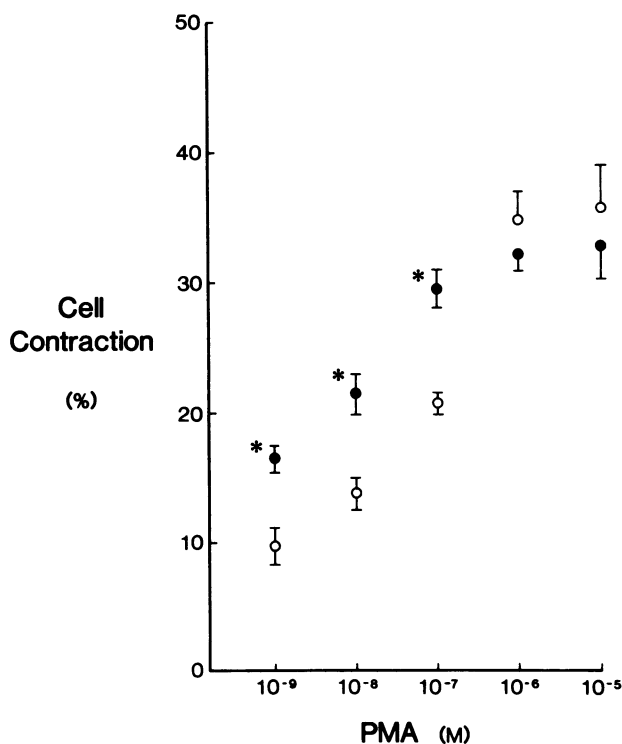

Figure 8. Potentiating effect of ouabain on PMA-induced sustained cellular contractile response in rat VSMC in culture. (o) Vehicle and (●) 10^{-5} M ouabain. Values are expressed as mean±SEM ($n = 6$). *$P < 0.01$ (vs. vehicle).

activation as assessed by IP_3 concentrations. Since either the calcium entry blocker, verapamil, or Ca^{2+}-free buffer, which completely blocks cellular Ca^{2+} uptake, abolished the potentiating effect of ouabain on the AVP-induced mobilization of $[Ca^{2+}]_i$, the increase in the AVP-mobilized $[Ca^{2+}]_i$ in the cells preincubated with ouabain appeared to be dependent on enhanced basal and AVP-stimulated cellular Ca^{2+} uptake by ouabain.

In addition to enhancing $[Ca^{2+}]_i$, cellular Ca^{2+} uptake potentiated by ouabain may also enhance the effect of protein kinase C and thus sustained VSMC contraction. Specifically, the activation of phospholipase C by AVP produces not only IP_3 but also diacylglycerol, a physiological activator of protein kinase C (37), and the activation of protein kinase C is involved in the sustained phase of vascular smooth muscle contraction (39–45). Recent studies in cultured rat VSMC from our laboratory have demonstrated that both PMA and dioctanoylglycerol cause the sustained vascular smooth muscle contractile response in the absence of a detectable rise in $[Ca^{2+}]_i$ (31). Phorbol esters are also known to increase the affinity of protein kinase C for $[Ca^{2+}]_i$ so that the activation of this enzyme occurs at basal $[Ca^{2+}]_i$ concentration (46–49). Moreover, the preincubation of VSMC with 10^{-5} M ouabain for 60 min increased basal $[Ca^{2+}]_i$ concentration to a similar concentration as observed with 10^{-9} M AVP. On this background, the effect of ouabain on the contractile response of VSMC to PMA was investigated as a means to examine whether the effect of inhibition of Na^+/K^+-ATPase on AVP-induced cellular contraction might involve an enhancement of protein kinase C activity. The results demonstrated that the preincubation of VSMC with 10^{-5} M ouabain for 60 min at 37°C enhanced the sustained VSMC contraction due to submaximal, but not maximal, doses of PMA. This finding is compatible with the observation that a Ca^{2+} ionophore also enhances the contractile response to PMA (31). These results therefore suggest that the effect of Na^+/K^+-ATPase inhibition to increase the AVP-induced sustained cellular contractile response may involve an enhancement of protein kinase C activity.

In conclusion, the present results suggest that an increase in cellular Ca^{2+} uptake induced by the inhibition of Na^+/K^+-ATPase may enhance the cellular contractile response to AVP by (*a*) increasing the mobilization of $[Ca^{2+}]_i$ in the absence of a change in receptor binding or transmembrane signal transduction, and (*b*) enhancing protein kinase C activation. These findings provide potential insights into the effect of circulating Na^+/K^+-ATPase inhibitors to enhance the pressor activity of endogenous vasoconstrictors and the effect of calcium channel blockers to protect against cardiac glycoside intoxication (5, 50, 51).

Acknowledgments

References

1. De Wardener, H. E., and G. A. MacGregor. 1980. Dahl's hypothesis that a saluretic substance may be responsible for a sustained

rise in arterial pressure: Its possible role in essential hypertension. *Kidney Int.* 18:1–9.

2. Blaustein, M. P., and J. M. Hamlyn. 1984. Sodium transport inhibition, cell calcium, and hypertension: the natriuretic hormone/Na^+-Ca^{2+} exchange/hypertension hypothesis. *Am. J. Med.* 77:45–59.

3. Blaustein, M. P. 1977. Sodium ions, calcium ions, blood pressure regulation, and hypertension: a reassessment and a hypothesis. *Am. J. Physiol.* 232:C165–C173.

4. Kazazoglou, T., J.-F. Renaud, B. Rossi, and M. Lazdunski. 1983. Two classes of ouabain receptors in chick ventricular cardiac cells and their relation to (Na^+,K^+)-ATPase inhibition, intracellular Na^+ accumulation, Ca^{2+} influx, and cardiotonic effect. *J. Biol. Chem.* 258:12163–12170.

5. Mulvany, M. J. 1984. Effect of electrolyte transport on the response of arteriolar smooth muscle. *J. Cardiovasc. Pharmacol.* 6:S82–S87.

6. Lee, H.-C., and W. T. Clusin. 1987. Na^+/Ca^{2+} exchange in cardiac myocytes: Effect of ouabain on voltage dependence. *Biophys. J.* 51:169–176.

7. Nabel, E. G., B. C. Berk, T. A. Brock, and T. W. Smith. 1988. Na^+-Ca^{2+} exchange in cultured vascular smooth muscle cells. *Circ. Res.* 62:486–493.

8. Poston, L., R. B. Sewell, S. P. Wilkinson, P. J. Richardson, R. Williams, E. M. Clarkson, G. A. MacGregor, and H. E. de Wardener. 1981. Evidence for a circulating sodium transport inhibitor in essential hypertension. *Br. Med. J.* 282:847–849.

9. MacGregor, G. A., S. Fenton, J. Alaghband-Zadeh, N. Markandu, J. E. Roulston, and H. E. de Wardener. 1981. Evidence for a raised concentration of a circulating sodium transport inhibitor in essential hypertension. *Br. Med. J.* 283:1355–1357.

10. Hamlyn, J. M., R. Ringel, J. Schaeffer, P. D. Levinson, B. P. Hamilton, A. A. Kowarski, and M. P. Blaustein. 1982. A circulating inhibitor of $(Na^+ + K^+)$ ATPase associated with essential hypertension. *Nature (Lond.).* 300:650–652.

11. Devynck, M.-A., M.-G. Pernollet, J. B. Rosenfeld, and P. Meyer. 1983. Measurement of digitalis-like compound in plasma: Application in studies of essential hypertension. *Br. Med. J.* 287:631–634.

12. De Thé, H., M.-A. Devynck, J. Rosenfeld, M.-G. Pernollet, J.-L. Elghozi, and P. Meyer. 1984. Plasma sodium pump inhibitor in essential hypertension and normotensive subjects with hypertensive heredity. *J. Cardiovasc. Pharmacol.* 6(Suppl. II):S49–S54.

13. Sagnella, G. A., J. C. Jones, A. C. Shore, N. D. Markandu, and G. A. MacGregor. 1986. Evidence for increased levels of a circulating ouabainlike factor in essential hypertension. *Hypertension.* 8:433–437.

14. Lindner, A., M. Kenny, and A. J. Meacham. 1987. Effects of a circulating factor in patients with essential hypertension on intracellular free calcium in normal platelets. *N. Engl. J. Med.* 316:509–513.

15. Gonick, H. C., H. J. Kramer, W. Paul, and E. Lu. 1977. Circulating inhibitor of sodium-potassium-activated adenosine triphosphatase after expansion of extracellular fluid volume in rats. *Clin. Sci. Mol. Med.* 53:329–334.

16. Gruber, K. A., J. M. Whitaker, and V. M. Buckalew, Jr. 1980. Endogenous digitalis-like substance in plasma of volume-expanded dogs. *Nature (Lond.).* 287:743–745.

17. Pamnani, M., S. Huot, J. Buggy, D. Clough, and F. Haddy. 1981. Demonstration of a humoral inhibitor of the Na^+-K^+ pump in some models of experimental hypertension. *Hypertension.* 3:(Suppl. II):II-96–II-101.

18. Gruber, K. A., L. L. Rudel, and B. C. Bullock. 1982. Increased circulating levels of an endogenous digoxin-like factor in hypertensive monkeys. *Hypertension.* 4:348–354.

19. Kojima, I. 1984. Circulating digitalis-like substance is increased in DOCA-salt hypertension. *Biochem. Biophys. Res. Commun.* 122:129–136.

20. Haddy, F. J. 1983. Potassium effects on contraction in arterial smooth muscle mediated by Na^+, K^+-ATPase. *Fed. Proc.* 42:239–245.

21. Blaustein, M. P., and J. M. Hamlyn. 1983. Role of a natriuretic factor in essential hypertension: A hypothesis. *Ann. Intern. Med.* 98(Suppl.):785–792.

22. Smith, T. W. 1988. Digitalis: mechanisms of action and clinical use. *N. Engl. J. Med.* 318:358–365.

23. Meyer-Lehnert, H., P. Tsai, and R. W. Schrier. 1987. Atrial natriuretic factor inhibits arginine vasopressin-stimulated Ca^{2+} fluxes and cell contraction in vascular smooth muscle cells. *Klin. Wochenschr.* 65(Suppl. VIII):115–121.

24. Caramelo, C., P. Tsai, and R. W. Schrier. 1988. Mechanisms of the cellular effect of phorbol esters on the action of arginine vasopressin and angiotensin II on vascular smooth muscle cells. *Biochem. J.* 254:625–629.

25. Meyer-Lehnert, H., C. Caramelo, P. Tsai, and R. W. Schrier. 1988. Interaction of atriopeptin III and vasopressin on calcium kinetics and contraction of aortic smooth muscle cells. *J. Clin. Invest.* 82:1407–1414.

26. Chamley, J. H., G. R. Campbell, and J. D. McConnel. 1977. Comparison of vascular smooth muscle cells from adult human, monkey and rabbit in primary culture and in subculture. *Cell Tissue Res.* 177:503–522.

27. Takeda, K., H. Meyer-Lehnert, J. K. Kim, and R. W. Schrier. 1988. AVP-induced Ca fluxes and contraction of rat glomerular mesangial cells. *Am. J. Physiol.* 255:F142–F150.

28. Lowry, O. H., N. J. Rosebrough, A. L. Farr, and R. J. Randall. 1951. Protein measurement with the Folin phenol reagent. *J. Biol. Chem.* 193:265–275.

29. Grynkiewicz, G., M. Poenie, and R. Y. Tsien. 1985. A new generation of Ca^{2+} indicators with greatly improved fluorescence properties. *J. Biol. Chem.* 260:3440–3450.

30. Tsai, P., K. Okada, C. Caramelo, and R. W. Schrier. 1989. Characterization of arginine vasopressin V_1 receptor in rat vascular smooth muscle cells in culture. *Clin. Res.* 37:503A. (Abstr.)

31. Caramelo, C., K. Okada, P. Tsai, and R. W. Schrier. 1989. Phorbol esters and arginine vasopressin in vascular smooth muscle cell activation. *Am. J. Physiol.* 256:F875–F881.

32. Takhar, A. P. S., and C. J. Kirk. 1981. Stimulation of inorganic-phosphate incorporation into phosphatidylinositol in rat thoracic aorta mediated through V_1-vasopressin receptors. *Biochem. J.* 194:167–172.

33. Charest, R., V. Prpic, J. H. Exton, and P. F. Blackmore. 1985. Stimulation of inositol trisphosphate formation in hepatocytes by vasopressin, adrenaline and angiotensin II and its relationship to changes in cytosolic free Ca^{2+}. *Biochem. J.* 227:79–90.

34. Nabika, T., P. A. Velletri, W. Lovenberg, and M. A. Beaven. 1985. Increase in cytosolic calcium and phosphoinositide metabolism induced by angiotensin II and [Arg] vasopressin in vascular smooth muscle cells. *J. Biol. Chem.* 260:4661–4670.

35. Burgess, G. M., P. P. Godfrey, J. S. McKinney, M. J. Berridge, R. F. Irvine, and J. W. Putney, Jr. 1984. The second messenger linking receptor activation to internal Ca release in liver. *Nature (Lond.).* 309:63–66.

36. Monck, J. R., E. E. Reynolds, A. P. Thomas, and J. R. Williamson. 1988. Novel kinetics of single cell Ca^{2+} transients in stimulated hepatocytes and A10 cells measured using fura-2 and fluorescent videomicroscopy. *J. Biol. Chem.* 263:4569–4575.

37. Grillone, L. R., M. A. Clark, R. W. Godfrey, F. Stassen, and S. T. Crooke. 1988. Vasopressin induces V_1 receptors to activate phosphatidylinositol- and phosphatidylcholine-specific phospholipase C and stimulates the release of arachidonic acid by at least two pathways in the smooth muscle cell line, A-10. *J. Biol. Chem.* 263:2658–2663.

38. Nishizuka, Y. 1984. The role of protein kinase C in cell surface signal transduction and tumor promotion. *Nature (Lond.).* 308:693–698.

39. Rasmussen, H. 1986. The calcium messenger system. *N. Engl. J. Med.* 314:1094–1101.

40. Rasmussen, H. 1986. The calcium messenger system. *N. Engl. J. Med.* 314:1164–1170.

41. Forder, J., A. Scriabine, and H. Rasmussen. 1985. Plasma membrane calcium flux, protein kinase C activation and smooth muscle contraction. *J. Pharmacol. Exp. Ther.* 235:267–273.

42. Baraban, J. M., R. J. Gould, S. J. Peroutka, and S. H. Snyder. 1985. Phorbol ester effects on neurotransmission: interaction with neurotransmitters and calcium in smooth muscle. *Proc. Natl. Acad. Sci. USA.* 82:604–607.

43. Park, S., and H. Rasmussen. 1985. Activation of tracheal smooth muscle contraction: synergism between Ca^{2+} and activators of protein kinase C. *Proc. Natl. Acad. Sci. USA.* 82:8835–8839.

44. Itoh, H., and K. Lederis. 1987. Contraction of rat thoracic aorta strips induced by phorbol 12-myristate 13-acetate. *Am. J. Physiol.* 252:C244–C247.

45. Wagner, B., C. Schächtele, and D. Marmé. 1987. Phorbol 12,13-dibutyrate-induced contraction of isolated rabbit vascular smooth muscle. *Eur. J. Pharmacol.* 140:227–232.

46. Kishimoto, A., Y. Takai, T. Mori, U. Kikkawa, and Y. Nishizuka. 1980. Activation of calcium and phospholipid-dependent pro-tein kinase by diacylglycerol, its possible relation to phosphatidylino-sitol turnover. *J. Biol. Chem.* 255:2273–2276.

47. Castagna, M., Y. Takai, K. Kaibuchi, K. Sano, U. Kikkawa, and Y. Nishizuka. 1982. Direct activation of calcium-activated, phos-pholipid-dependent protein kinase by tumor-promoting phorbol esters. *J. Biol. Chem.* 257:7847–7851.

48. Kikkawa, U., Y. Takai, R. Minakuchi, S. Inohara, and Y. Nishizuka. 1982. Calcium-activated, phospholipid-dependent protein kinase from rat brain. *J. Biol. Chem.* 257:13341–13348.

49. Jiang, M. J., and K. G. Morgan. 1987. Intracellular calcium levels in phorbol ester-induced contractions of vascular muscle. *Am. J. Physiol.* 253:H1365–H1371.

50. Ferrier, G. R. 1977. Digitalis arrhythmias: Role of oscillatory afterpotentials. *Prog. Cardiovasc. Dis.* 19:459–474.

51. Jonkman, F. A. M., W. G. M. Boddeke, and P. A. van Zwieten. 1986. Protective activity of calcium entry blockers against ouabain intoxication in anesthetized guinea pigs. *J. Cardiovasc. Pharmacol.* 8:1009–1013.