The Pump, the Exchanger, and Endogenous Ouabain
Signaling Mechanisms That Link Salt Retention to Hypertension


The central roles of salt (NaCl) and the kidneys in the pathogenesis of most forms of hypertension are well established.1,2 The linkage between NaCl retention and blood pressure (BP) elevation is often referred to as “whole body autorregulation.”3,4 Surprisingly, however, the precise mechanisms that underlie this linkage (ie, the signaling pathway) have escaped elucidation. Here, we examined the evidence that endogenous ouabain (EO), Na+/pumps (Na,K-ATPase), and the Na/Ca exchanger (NCX) are critical molecular mechanisms in this pathway.

Ca2+ and the Control of Myogenic Tone
At constant cardiac output (CO), mean arterial BP=CO×TPR (where TPR is total peripheral vascular resistance).5 In most (chronic) hypertension, in humans and animals, the CO is relatively normal, and the high BP is maintained by an elevated TPR.1,4 TPR is controlled dynamically by vasoconstriction/dilation in small “resistance” arteries, which exhibit tonic constriction (“tone”). This can be studied in isolated, cannulated small arteries that develop spontaneous (myogenic) tone (MT),6 under constant or increasing intraluminal pressure. Indeed, the level of tone in isolated arteries “is often comparable to that observed in the same vessels in vivo,”7 and may even be used to predict BP changes8 (see below).

MT is triggered by Ca2+ entry, primarily through voltage-gated Ca2+ channels in arterial smooth muscle (ASM) cells,6 and contraction is activated by the rise in cytosolic Ca2+ concentration ([Ca2+]CYT).8 In NaCl-dependent hypertension, the enhanced vasoconstriction and increased tone and TPR are, at least in part, functional and reversible phenomena.9 Numerous mechanisms contribute to the regulation of myocyte [Ca2+]CYT and vasoconstriction, but the plasma membrane (PM) NCX provides an unique, direct link between Na+ and [Ca2+]CYT and, thus, Ca2+ signaling and contraction in ASM cells.10 NCX-mediated Ca2+ transport is governed by the Na+/electrochemical gradient generated by the PM Na+/pump.

We proposed that an endogenous Na+/pump inhibitor, ie, a ouabain-like compound, with vasotonic action might be secreted in response to NaCl retention.11 In other words, this substance might be a missing hormonal link between NaCl retention and the increased TPR and hypertension. Conservation of the high-affinity ouabain binding site amino acid sequence in mammalian evolution (see below) implies that there must be an endogenous ligand for this site. Partial Na+/pump inhibition by the endogenous inhibitor should promote the net gain of Ca2+ via the myocyte NCX and thereby augment Ca2+ signaling and vasoconstriction.10,11

Endogenous Ouabain
These ideas triggered an intense international search for the postulated endogenous Na+/pump inhibitor, a ligand for the ouabain/digoxin binding site of the pump, that might mediate the vascular response. In 1991, our group purified EO from human plasma; the substance was identified as ouabain by mass spectroscopy.12 It is now possible to quantify EO by liquid chromatography-tandem mass spectroscopy starting from small (1-mL) samples of human or animal plasma.13 The liquid chromatography-tandem mass spectroscopy spectra from human and rodent plasma extracts exhibit a major product ion at a mass:charge ratio of 445 (Figure S1 to S3, available in the online data supplement at http://hyper.ahajournals.org); this is the lithiated glycone of EO (ie, lithiated ouabagenin). The possibility that EO might be the 11β isomer of ouabain14 is excluded, because the 11-epimers of ouabain have different chromato-graphic behavior.15

Rat adrenal cortex is highly enriched with EO, and human and cow adrenals also contain very high levels.12 Bilateral adrenalectomy causes a large decline in rat plasma EO, whereas treatment of uninephrectomized rats with deoxycorticosterone acetate (DOCA)+NaCl increases plasma EO >10-fold, and

Received October 9, 2008; first decision October 30, 2008; revision accepted November 22, 2008.

From the Departments of Physiology (M.P.B., J.Z., H.S., H.R., S.P.K., M.I., W.G.W., J.M.H.) and Medicine (M.P.B., L.C.) and the Center for Heart, Hypertension, and Kidney Disease (M.P.B., J.Z., H.S., H.R., S.P.K., M.I., W.G.W., J.M.H.), University of Maryland School of Medicine, Baltimore; the Department of Pharmacology (T.I.), Fukuoka University School of Medicine, Fukuoka, Japan; the Department of Biomedical Sciences (M.I.), College of Veterinary Medicine, Cornell University, Ithaca, NY; the Department of Molecular Genetics, Biochemistry, and Microbiology (J.B.L.), University of Cincinnati College of Medicine, Cincinnati, Ohio; and the Department of Physiology and the Cardiovascular Research Laboratories (K.D.P.), David Geffen School of Medicine, University of California, Los Angeles.

Correspondence to Mordecai P. Blaustein, Department of Physiology, University of Maryland School of Medicine, 655 W Baltimore St, Baltimore, MD 21201. E-mail mblaustein@som.umaryland.edu

Hypertension is available at http://hyper.ahajournals.org

DOI: 10.1161/HYPERTENSIONAHA.108.119974
significantly elevates BP.12 These data imply that EO is primarily an adrenocortical hormone, although it may also be synthesized in, and secreted by, the hypothalamus.16

Studies of humans and intact animals, and of adrenocortical cell cultures, reveal that EO is synthesized in the adrenal cortex and that its synthesis and secretion are stimulated by adrenocorticotropic hormone (corticotropin [ACTH]).12,17–19 In humans19 and animals,18 ACTH-induced hypertension is associated with elevation of EO. Indeed, a preliminary report indicates that certain rare adrenocortical tumors, which are associated with severe hypertension, may produce prodigious amounts of EO.20

Approximately 50% of humans with untreated essential hypertension and a majority of patients with adrenocortical adenomas and hypertension have significantly elevated plasma EO; moreover, BP correlates directly with plasma EO.21 Even in normal human subjects, a high-NaCl diet elevates plasma EO,22 and a 10-minute infusion of low-dose ouabain increases vascular resistance and elevates BP for >60 minutes.23

Plasma EO levels are elevated in several rodent NaCl-sensitive hypertension models.12,24,25 and chronic administration of low-dose ouabain to normal rodents usually induces hypertension in 1 to 3 weeks.26,27 Furthermore, subpressor doses of ouabain and DOCA act synergistically to induce hypertension.28 Ouabain-induced BP elevation in rodents is markedly reduced.33 Ouabain also does not induce hypertension in sheep34 or in mineralocorticoid-resistant35 Long-Evans rats.36 These apparent exceptions may, however, yield novel information to help clarify the relationship between EO and hypertension.

Many of the findings cited above provide strong evidence that circulating EO has a key role in the pathogenesis of NaCl-sensitive hypertension. Other studies suggest, however, that brain, not plasma, EO,16 or even marinobufagenin,37 may be important.

Surprisingly, digoxin, another cardiotonic steroid and Na,K-ATPase inhibitor, does not induce hypertension in rodents.26,38 Also, Digitalis glycosides do not elevate BP in patients treated for congestive heart failure or cardiac arrhythmias.39 Remarkably, digoxin actually lowers BP in ouabain-hypertensive rats36 and in many patients with essential hypertension.40 Thus, Strophanthus glycosides, such as ouabain, may interact differently with Na+ pumps than do the structurally distinct Digitalis glycosides. Moreover, many observations now indicate that EO is a growth hormone and that it may participate in a variety of kinase-mediated and other signaling pathways independent of its effects on Na+ pump–mediated Na+ transport.41,42 EO may, therefore, contribute to vascular remodeling and target organ damage in hypertension. Clearly, there is much that we do not yet understand about the physiology and pharmacology of these agents.

Membrane Microdomains: A Structural Basis for the Action of Ouabain

Na+ pumps are αβ heterodimers. The catalytic subunit, α, contains the Na+, K+, MgATP, and ouabain binding sites and is phosphorylated during each pump cycle.43 β is essential for pump function; it stabilizes the α subunit conformation and chaperones the αβ complex to the PM.23,44 In some tissues, a third subunit, γ, may help to regulate Na+ pump activity.44 There are 4 mammalian α subunit isoforms (α1 to α4); they are products of different genes but have ~90% sequence identity, different expression patterns,45 and different kinetics,46 and they are differently regulated.43,47 All of the cells express Na+ pumps with an α1 subunit and Na+ pumps with another α isoform,43,45 Skeletal, cardiac, and SMs, eg, express Na+ pumps with an α2 subunit, as well as pumps with an α1; most neurons express α1 and α3.46 Renal epithelia express predominantly (>90% to 95%) Na+ pumps with α1, which mediate the final step in net transepithelial Na+ reabsorption.47

The functions of the different α subunit isoforms were elucidated by the discovery that, in a variety of cell types, Na+ pumps with an α2 or α3 subunit are confined to PM microdomains situated adjacent to “junctional” sarcoplasmic/endoplasmic reticulum (jS/ER; Figure 1).45 Here, these Na+ pumps colocalize with NCX, which are confined to the same PM microdomains.45 Na+ pumps with an α1 subunit are more widely distributed in the PM but are apparently excluded from these microdomains.45 Importantly, the PM microdomains are separated by only 12 to 20 nm from the jS/ER,45 and these structures form a functional unit, termed the “PLasmERosome.”45 The volume of cytosol in the junctional space between the PM and jS/ER of a single PLasmERosome is only on the order of 10-19 to 10-18 L,45 and diffusion of Na+ and Ca2+ between this space and bulk cytosol is restricted. Thus, standing Na+ and Ca2+ concentration gradients between these compartments and bulk cytosol can be maintained.52-54

Differences in Na+ pump α subunit isoform kinetics play a critical role in PLasmERosome function. The rodent α1 isoform has unusually low affinity for ouabain (K<sub>ouabain</sub> >100 μmol/L versus <0.05 μmol/L in humans) so that nanomolar ouabain inhibits only the α2 Na+ pumps in rodent arterial myocyte PLasmERosomes.7 Even in humans, however, where α1 Na+ pumps have high affinity for ouabain, partial inhibition of Na+ pumps by nanomolar ouabain will raise [Na+] in the junctional space much more than in bulk cytosol. The reason is that the affinity of α2 Na+ pumps for Na+ is much lower (K<sub>Na</sub> = 22 mmol/L) than is the affinity of α1 Na+ pumps (K<sub>Na</sub> = 12 mmol/L).46

The widespread distribution of α1 Na+ pumps implies that they have a “housekeeping” function: they control, primarily, [Na+] in bulk cytosol. In contrast, the pumps with an α2 (eg, in SM) or α3 catalytic subunit regulate local [Na+] in the junctional space. Thus, these α2/α3 Na+ pumps control the local Na+ electrochemical gradient that influences Ca2+ transport by NCX. This organizational arrangement (Figure 1) uniquely links cell Ca2+ to Na+ metabolism. The transporters in the PLasmERosome regulate not only [Ca2+] in the junctional space but S/ER Ca2+ stores and global Ca2+
signaling in the cells as well. Modulation of $\alpha_2$ Na$^+$ pumps in arterial myocyte PLasmERosomes by EO can, therefore, influence arterial tone and BP. Below, we have summarized recent studies in which genetic engineering and pharmacological manipulation of mouse Na$^+$ pumps and NCX (Figure 2) have been used to examine the roles of these transporters in the long-term control of BP.

**Downstream Effector Mechanisms**

$\alpha_2$ Na$^+$ Pumps

As already noted, chronic administration of exogenous ouabain induces hypertension in rodents. The questions we now address are: how does ouabain (or EO) elevate BP, and is it because of inhibition of SM $\alpha_2$ Na$^+$ pumps, as implied above?

---

**Steps in the Pathogenesis of Salt-dependent Hypertension**

**Etiology:**

- **NaCl Intake** or Renal Na$^+$ Excretion or Na$^+$ Re-absorption
- Na(Cl) and Water Retention

**Interventions:**

- ACTH
- Exogenous Ouabain
  - Ouabain Antagonists
  - "Digibind"
- Na$^+$ Pump $\alpha_2^{2R}$, $\alpha_2^{2smDN}$
- Na$^+$ Pump $\alpha_2^{2smMTV}$
- NCX Inhibitors
  (e.g., SEA0400)
- NCX1$^{3SM/L}$
- NCX1$^{3smTg}$
- Na/Ca Exchange ($\uparrow$ Ca$^{2+}$ Entry)
  - [Ca$^{2+}$]CYT

**Red: block BP elevation or lower BP**

**Green: elevate BP**

**KIDNEYS**

- Plasma Volume
- Plasma Endogenous Ouabain (EO)

**ADRENAL CORTEX**

- Na$^+$ Pump $\alpha_2$ Activity
- Na$^+$ Pump $\alpha_2$ Activity

**ARTERIAL SMOOTH MUSCLE**

- Na/Ca Exchange ($\uparrow$ Ca$^{2+}$ Entry)
- [Ca$^{2+}$]CYT
- Ca$^{2+}$ Signaling
- Vascular Tone and Contractility
- Blood Pressure

**Figure 1.** Model of the PM-JSR/ER region, the PLasmERosome, showing the location of key transport proteins involved in local control of JS/ER Ca$^{2+}$ stores and Ca$^{2+}$ signaling. The PLasmERosome consists of a PM microdomain, the adjacent JS/ER, and the intervening “diffusion-restricted” junctional space (J). The PM microdomain contains $\alpha_2$ (in SM) or $\alpha_3$ Na$^+$ pumps, NCX, and receptor and store-operated channels (ROCs and SOCs, composed of various transient receptor potential channel proteins [TRPCs]). The JS/ER membrane contains SR Ca$^{2+}$ pumps (SERCA), inositol trisphosphate receptors (IP$_3$Rs), and ryanodine receptors (RYRs). Other regions of the PM contain $\alpha_1$ Na$^+$ pumps and Ca$^{2+}$ pumps (PMCA$s$), as well as agonist receptors (AR$s$; which are G protein–coupled receptors, [GPCRs]). Activation of GPCRs and release of G proteins (GPs) stimulate phospholipase C (PLC) to produce IP$_3$ and diacylglycerol (DAG). DAG may activate ROCs directly. Na$^+$ may enter locally, through ROCs, SOCs, or stretch-activated channels (not shown) to promote Ca$^{2+}$ entry via NCX. Shading indicates relative Na$^+$ and/or Ca$^{2+}$ concentrations. (Reprinted with permission).

**Figure 2.** Proposed sequence of steps in the pathogenesis of NaCl-dependent hypertension. The “interventions,” listed at the left, indicate some of the pharmacological and genetic manipulations that were used to test the proposed sequence, as discussed in this review. Genotype nomenclature for genetically engineered mice is given in the text and in legends for Figures 3 and 4. Interventions shown in green increase traffic through the pathway and promote BP elevation; those shown in red block traffic through the pathway and prevent BP elevation or lower BP. Modified from Reference 7.
If circulating ouabain (or EO) elevates BP by inhibiting arterial myocyte α2 Na⁺ pumps, reduced expression of α2 Na⁺ pumps should have a similar effect. Therefore, we studied mice with a null mutation in either the α1 or α2 Na⁺ pump.66 Heterozygous (α1+/− and α2+/− or α2+/−; see Figure 2), but not homozygous, null mutants survive, and they express ≈50% of the normal complement of α1 or α2 pump protein, respectively, in ASM.7 Isolated mesenteric small arteries from the α2+/− but not α1+/− mice exhibit augmented myogenic reactivity in response to stepwise increases in intraluminal pressure and significantly elevated MT when pressurized to 70 mm Hg.7 Nanomolar ouabain also augments myogenic reactivity and increases MT with an EC₅₀ of ≈1.3 nmol/L.7 Consistent with these effects in isolated arteries, α2+/− but not α1+/− mice have significantly elevated BP (Figure 3).7 Moreover, the α2+/− mice are “NaCl sensitive”: a high-NaCl diet increases BP much more in these mice than in their wild-type (WT) littermates (Figure 4).48 Clearly, ACTH-induced hypertension depends on the existence of a high-affinity cardiotonic steroid binding site on the α2 Na⁺ pump and on a water-soluble ligand that binds to this site. The plasma level of this ligand (presumably EO) was increased by ACTH and, like ouabain, bound to Digibind with high affinity.48 Moreover, Digibind counteracted the augmentation of MT by nanomolar ouabain but not the (ouabain-independent) augmenting effect of reduced α2 expression on MT.7 Rostafuroxin also lowered BP in ouabain-induced hypertension29 and in ≈30% of humans with essential hypertension.29

As an alternative, in a knockin study, 2 amino acids in the α2 Na⁺ pump ouabain-binding site were mutated to reduce, markedly, the affinity of the α2 pump for ouabain.18,48 Mice that expressed ouabain-resistant α2 pumps (α2K/R) were resistant to ACTH-induced hypertension (Figure 4),18 as well as to ouabain-induced hypertension.48 Moreover, Digibind prevented the ouabain-induced elevation of BP in the WT mice (Figure 4).48 Clearly, ACTH-induced hypertension depends on the existence of a high-affinity cardiotonic steroid binding site on the α2 Na⁺ pump and on a water-soluble ligand that binds to this site. The plasma level of this ligand (presumably EO) was increased by ACTH and, like ouabain, bound to Digibind with high affinity.48

These genetic engineering studies reveal that arterial myocyte α2 Na⁺ pumps mediate the effects of EO and play a role in the long-term regulation of BP. Genetically or pharmacologically reduced α2 activity elevates BP, whereas increased α2 activity lowers BP (Figures 2 and 3). The next question is: by what specific mechanism does the altered α2 Na⁺ pump activity influence BP? The answer appears to lie in Na/Ca exchange.
NCX Type 1

Na/Ca exchange uniquely and directly links Na\(^+\) to Ca\(^{2+}\) metabolism and is a distal regulator of cytosolic Ca\(^{2+}\). There are 2 classes of NCXs, those that cotransport K\(^+\) with Ca\(^{2+}\) and those that do not.\(^6\)

The predominant exchanger in arterial myocytes is K\(^+\)-independent NCX, although NCX that cotransports K\(^+\) with Ca\(^{2+}\) has also been detected.\(^6\) There are 3 mammalian NCX isoforms (NCX1 to NCX3), each the product of a different gene.\(^6\) NCX1, which is expressed in ASM, has multiple splice variants; NCX1.3 is the main variant in arterial myocytes.\(^6\)

Inhibition of Na\(^+\) pumps by nanomolar ouabain augments Ca\(^{2+}\) signaling without elevating bulk cytosolic Na\(^+\) in primary cultured rat arterial myocytes.\(^6\) Even knockout of α2 Na\(^+\) pumps in cultured cells (astrocytes) has only a minimal effect on bulk cytosolic Na\(^+\) but a large effect on Ca\(^{2+}\) signaling.\(^6\) These findings are consistent with a functional linkage between α2 (but not α1) Na\(^+\) pumps and NCX1, and local reduction of the trans-PM Na\(^+\) gradient when α2 activity is reduced, as implied by the PLoasmERosome model (Figure 1). Moreover, recent pharmacological and genetic engineering studies now reveal that NCX1 influences not only arterial myocyte Ca\(^{2+}\) metabolism but also long-term vascular tone and BP as well.

Mice in which NCX1 is overexpressed in SM with an α-actin promoter (NCX1\(^{SM/T8}\)) have elevated BP that is markedly increased by a high-NaCl diet; ie, the mice are NaCl sensitive (Figure 3).\(^6\) The elevated BP in the NCX1 overexpressors on high dietary NaCl is abolished by SEA0400, a selective NCX inhibitor,\(^6\) but not if the overexpressed NCX1 contains a G833C mutation,\(^6\) which specifically abrogates the action of SEA0400.\(^6\)

To perform the converse experiment, mice with floxed NCX1 (NCX1\(^{FLX/FLX}\)) were crossed with mice containing a Cre recombinase gene under the control of the SM myosin heavy chain promoter to generate SM-specific NCX1 knockout (NCX1\(^{SM-/—}\)) mice. NCX1\(^{SM-/—}\) mice have abnormally low BP (Figure 3), and isolated, pressurized small arteries from these mice have abnormally low MT.\(^7\) Indeed, SEA0400 also lowers BP by ≈5 to 10 mm Hg in WT mice\(^6\) and reduces MT by ≈10% in isolated arteries from these mice.\(^7\) Thus, NCX1 activity apparently makes a modest but direct contribution to normal MT and BP. SEA0400 also attenuates the increased MT in arteries from α2\(^{-/-}\) mice,\(^7\) indicating that NCX1 mediates effects distal to α2 Na\(^+\) pumps. The BP and MT data from α2\(^{-/-}\) and NCX1\(^{SM-/—}\) mice support the view that MT in isolated arteries is an in vitro reflection of BP and, most likely, TPR.

The mice with genetically engineered NCX1 demonstrate that this exchanger contributes to long-term BP regulation: increased NCX1 expression increases BP, whereas knockout of NCX1 reduces BP (Figures 2 and 3). This conclusion is supported by the effects of NCX blockers in several rodent models of NaCl-dependent or ACTH-induced hypertension. In DOCA + NaCl hypertensive rats, spontaneously hypertensive rats, and the renin-dependent 2-kidney/1-clip rat,\(^8\) and the sensitivity of the contractile apparatus to that Ca\(^{2+}\).\(^7\) Furthermore, NCX1, under the control of the Na\(^+\) gradient generated by the adjacent α2 Na\(^+\) pumps, helps regulate myocyte Ca\(^{2+}\) ho-

Figure 5. Effects of low-dose ouabain and SEA0400 on [Ca\(^{2+}\)]\(_{cyt}\) and MT in mouse pressurized mesenteric small arteries. A, Simultaneous recording of fluorescence (F, in arbitrary units [a.u.], a measure of [Ca\(^{2+}\)]\(_{cyt}\)) and external diameter in a representative fluo-4-loaded normal mouse artery pressurized to 70 mm Hg. Bars at the top indicate periods of exposure to 100 nM ouabain, 300 nM SEA0400, and 0Ca medium (to determine passive diameter [PD]). B, Arrows in the black and white spinning disk confocal image at the left indicate fluorescence in individual myocytes of a longitudinal cross-section through 1 wall of the artery in A. Pseudocolor images of this artery wall were captured at the times indicated by arrows “a” (control MT), “b” (MT with ouabain), and “c” (MT with ouabain + SEA0400) in A; “L” is located in the artery lumen. C, Summary of normalized MT data from this and 5 other, similar experiments. *P < 0.05, ##P < 0.01 vs untreated control; **P < 0.01 vs ouabain alone. Corrected from Reference 66.
meostasis (Figure 1). For example, the nanomolar ouabain-induced increase in MT is associated with increased myocyte \([Ca^{2+}]_{i}\); conversely, reduction of MT by SEAO400 is associated with reduced myocyte \([Ca^{2+}]_{i}\) (Figure 5).\(^6\) Thus, it is apparent that \(\alpha2\) \(Na^+\) pumps and NCX1 are relatively distal mechanisms in the final common path that links NaCl to vasoconstriction and hypertension (Figure 2). Indeed, all upstream vasoconstrictor and vasodilator mechanisms (neural and humoral) must, inevitably, be influenced by the activity of these 2 transporters, because they regulate basal \([Ca^{2+}]_{i}\) in arterial myocytes.

An alternative suggestion is that activation of Rho/Rho kinase via the \(G_{12,-G_{13}}\)-mediated G protein–coupled receptor pathway, which modulates the \(Ca^{2+}\) sensitivity of the contractile apparatus in ASM,\(^7\) is selective for NaCl-dependent hypertension.\(^7\) Those authors, however, studied only an NaCl-dependent (DOCA+NaCl) mouse model; they did not test whether the \(G_{12,-G_{13}}\) pathway also operates in NaCl-independent forms of hypertension.\(^7\) In fact, interference with the \(G_{12,-G_{13}}\) pathway, whether at the agonist receptor level\(^7\) or at the level of the Rho kinase,\(^7\) lowers BP in NaCl-independent models, such as the stroke-prone spontaneously hypertensive rat\(^7\) and the NO synthase-inhibited rat.\(^7\) The \(G_{12,-G_{13}}\) pathway is, therefore, downstream and distinct from the key NaCl-sensitive steps in \(Na^+\)-dependent hypertension. Once NaCl-sensitive, NCX1-mediated \(Na^+/Ca^{2+}\) entry has occurred, the \(G_{12,-G_{13}}\) pathway helps modulate the increases in vascular tone and BP.

**Endgame: Na/Ca Exchange, \(Ca^{2+}\) Entry, and Myogenic Tone**

In the heart, the main role of NCX is to extrude, during diastole, much of the \(Ca^{2+}\) that enters through voltage-gated channels during systole.\(^8\) Consequently, reduced cardiac NCX1 function as a result, eg, of \(\alpha2\) \(Na^+\) pump inhibition by cardiotoxic steroids, is associated with \(Ca^{2+}\) gain and augmented signaling in cardiac myocytes. Therefore, it might at first seem surprising that ASM NCX1 contributes directly to vascular tone and that reduced expression or pharmacological inhibition of NCX1 in arterial myocytes lowers \([Ca^{2+}]_{i}\) and attenuates \(Ca^{2+}\) signaling (Figure 5). Indeed, \(Ca^{2+}\) entry via NCX has sometimes been called “reverse mode” exchange, implying, erroneously, that this is the backward or abnormal operation of the exchanger.\(^7\) NCX can transport \(Ca^{2+}\) in either direction across the PM,\(^8\) under the control of the local \(Na^+\) electrochemical gradient across the PM (Figure 1), and considerations of the electric component of this gradient are of paramount importance. In the heart, the driving force on the exchanger, ie, the difference between the prevailing membrane voltage \((V_M)\) and the NCX1 reversal potential \((E_{Na,Ca})\), which determines the direction of net \(Ca^{2+}\) movement, varies during the cardiac cycle. [For NCX1, which mediates the exchange of 3Na\(^+\) for 1\(Ca^{2+}\), \(E_{Na,Ca} = 3F\frac{E_{Na} - E_{Ca}}{F\frac{[Na]}{[Ca]}}\), where \(E_{Na}\) and \(E_{Ca}\) are, respectively, the equilibrium potentials for \(Na^+\) and \(Ca^{2+}\), \(E_{Na} = (RT/F) \ln \frac{[Na]}{[Ca]})\) and \(E_{Ca} = (RT/2F) \ln \frac{[Ca]_i}{[Ca]_o}\), and \(R, T, F\) are the gas constant, temperature in degrees Kelvin, and Faraday’s number, respectively.\(^7\)](https://hyper.ahajournals.org/content/296/2/256) The rapid membrane depolarization during the upstroke of the cardiac action potential, for example, rapidly switches NCX1 from the \(Ca^{2+}\) exit to \(Ca^{2+}\) entry mode, as the driving force, \(V_M - E_{Na,Ca}\), becomes positive. Then, as \(V_M\) repolarizes, during diastole, \(V_M - E_{Na,Ca}\) again becomes negative and favors \(Ca^{2+}\) exit.\(^7\)

A different situation exists in ASM, where changes in \(V_M\) are normally quite slow, and cells are often partially depolarized for very long periods of time.\(^7\) Here, intraluminal pressure in small arteries depolarizes the myocytes and activates dihydropyridine-sensitive \(L\)-type voltage-gated channels. Opening of stretch-activated nonselective cation channels\(^8\) may initiate the depolarization. This depolarization is insensitive to dihydropyridines: nifedipine blocks \(Ca^{2+}\) entry through \(L\)-type voltage-gated channels and reduces MT but has little effect on the pressure-activated depolarization.\(^7\) The \(Na^+\) entry through stretch-activated channels and consequent depolarization, as well as the rise in \([Ca^{2+}]_{i}\), should also have another, previously unrecognized consequence: they should promote \(Ca^{2+}\) entry via NCX1 and thereby contribute to MT. The reason is that the exchanger is activated by cytosolic \(Ca^{2+}\),\(^8\) and the rise in cytosolic \([Na^+]\) and the depolarization augment the \(Ca^{2+}\) entry mode of NCX1 by increasing the driving force, \(V_M - E_{Na,Ca}\). The implication is that both the \(L\)-type voltage-gated channels and NCX1 contribute to the maintenance of \(Na^+\) entry, elevated \([Ca^{2+}]_{i}\), and arterial tone when the arteries are pressurized.

“In My End Is My Beginning” (T.S. Eliot)

In this review, we have explored some of the critical steps that link NaCl retention with the long-term increase in TPR and elevation of BP. Recent results, especially those from chemical analyses of human and rodent plasma samples and from genetic engineering and pharmacological studies in rodents and rodent arteries are summarized above. These studies give new insight into some of the molecular events that help regulate cytosolic \(Ca^{2+}\) and vascular tone. The data supply compelling evidence that EO, SM \(\alpha2\) \(Na^+\) pumps, and NCX1 are key mechanisms in the pathway that leads from NaCl retention to hypertension (Figure 2).

These findings provide a framework, but the story is far from complete. For example, a key area where knowledge is lacking is at the early steps between NaCl retention and the release of EO, as indicated by the broken vertical lines in Figure 2. Also, Crowley et al\(^8\) demonstrated recently that the renal and extrarenal arteries make apparently independent (and equal) contributions to the long-term regulation of BP, but how the distal mechanisms, discussed above, affect the renal and extrarenal vasculature and renal function and thereby contribute to BP control is still unexplored. Finally, of course, a fundamental question is: what makes us NaCl sensitive in the first place? Hopefully, the progress outlined above will clarify new directions for hypertension research to help resolve these issues.

**Sources of Funding**

This work was supported by National Institutes of Health grants HL-45215 (to M.P.B.), HL-78870 (to M.P.B.), HL-45215 (to M.P.B.), HL-78870 (to M.P.B.), HL-65992 (to M.P.B.), HL-48509 (to J.B.L.), HL-75584 (to J.M.H.), a Japanese National Heart Institute KAKENHI grant on Priority Areas
Disclosures

None.

References

57. Song H, Lee MY, Kinsey SP, Weber DJ, Blaustein MP. An N-terminal
55. O'Brien WJ, Lingrel JB, Wallick ET. Ouabain binding kinetics of the rat
51. Arnon A, Hamlyn JM, Blaustein MP. Ouabain augments Ca\textsuperscript{2+}
in tissue and increased vascular contractility in vitro. Am J Physiol
56. Xin HB, Deng KY, Rishniw M, Ji G, Kotlikoff MI. Smooth muscle
59. Pritchard TJ, Bullard DP, Lynch RM, Lorenz JN, Paul RJ. Transgenic
52. Lee MY, Golovina VA, James PF, Lingrel JB, Blaustein MP. Ouabain augments Ca\textsuperscript{2+}
in arterial smooth muscle without raising cytosolic Na\textsuperscript{+}. Am J Physiol
53. Pritchard TJ, Bullard DP, Lynch RM, Lorenz JN, Paul RJ. Genomic
54. Golovina VA, Song H, Kinsey SP, Lingrel JB, Blaustein MP. Na\textsuperscript{+} pump
K, Komuro I, Katsuragi T. Salt-sensitive hypertension is triggered by
Ca\textsuperscript{2+} entry via Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger type-I in vascular smooth muscle.
58. Xin HB, Deng KY, Rishniw M, Ji G, Kotlikoff MI. Smooth muscle
61. Takahashi K, Takahashi T, Suzuki T, Ota T, Hamano-Takahashi A,
Onishi M, Tanaka Y, Kameo K, Baba A. SEA0400, a novel and selective
inhibitor of the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger, attenuates reperfusion injury in the
in vitro and in vivo cerebral ischemic models. J Pharmacol Exp Ther.
2001;298:249–256.
67. Matsuda T, Arakawa N, Takuma K, Kishida Y, Kawasaki Y, Sakaeu M,
Takahashi K, Takahashi T, Suzuki T, Ota T, Hamano-Takahashi A,
Onishi M, Tanaka Y, Kameo K, Baba A. SEA0400, a novel and selective
inhibitor of the Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger, attenuates reperfusion injury in the
in vitro and in vivo cerebral ischemic models. J Pharmacol Exp Ther.
2001;298:249–256.
The Pump, the Exchanger, and Endogenous Ouabain: Signaling Mechanisms That Link Salt Retention to Hypertension

Mordecai P. Blaustein, Jin Zhang, Ling Chen, Hong Song, Hema Raina, Stephen P. Kinsey, Michelle Izuka, Takahiro Iwamoto, Michael I. Kotlikoff, Jerry B. Lingrel, Kenneth D. Philipson, W. Gil Wier and John M. Hamlyn

_Hypertension_. 2009;53:291-298; originally published online December 22, 2008; doi: 10.1161/HYPERTENSIONAHA.108.119974

_Hypertension_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2008 American Heart Association, Inc. All rights reserved.
Print ISSN: 0194-911X. Online ISSN: 1524-4563

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://hyper.ahajournals.org/content/53/2/291

Data Supplement (unedited) at:
http://hyper.ahajournals.org/content/suppl/2008/12/22/HYPERTENSIONAHA.108.119974.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in _Hypertension_ can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to _Hypertension_ is online at:
http://hyper.ahajournals.org//subscriptions/
Online Supplement

The Pump, the Exchanger and Endogenous Ouabain: Signaling Mechanisms that Link Salt Retention to Hypertension

Mordecai P. Blaustein1,2, Jin Zhang1, Ling Chen2, Hong Song1, Hema Raina1, Stephen P. Kinsey1, Michelle Izuka1, Takahiro Iwamoto3, Michael I. Kotlikoff4, Jerry B. Lingrel5, Kenneth D. Philipson6, W. Gil Wier1 and John M. Hamlyn1

Departments of 1Physiology and 2Medicine, and the 1Center for Heart, Hypertension & Kidney Disease, University of Maryland School of Medicine, Baltimore, MD, USA;
3Department of Pharmacology, Fukuoka University School of Medicine, Fukuoka, Japan;
4Department of Biomedical Sciences, College of Veterinary Medicine, Cornell University, Ithaca, NY, USA;
5Department of Molecular Genetics, Biochemistry and Microbiology, University of Cincinnati College of Medicine, Cincinnati, OH, USA;
6Department of Physiology and the Cardiovascular Research Laboratories, David Geffen School of Medicine at UCLA, Los Angeles, CA, USA
**Assay of Endogenous and Exogenous Ouabain.**

Mass spectroscopy (MS) methods reveal that the endogenous ouabain (EO) isolated from human plasma has a mass of 584.2 daltons, identical to that obtained for plant-derived ouabain.¹ Advances in MS instrumentation, coupled with improved understanding of the behavior of various ion adducts of EO in the gas phase, now enable quantitation and fingerprinting of EO using small clinically relevant volumes of blood.² Examples of the liquid chromatography-tandem MS-MS (LC-MS-MS) of endogenous ouabain from 0.25 ml rat plasma and plant derived ouabain are shown in Supplementary Figures 1 and 2, respectively.

Inspection of the key ion current chromatograms and the MS-MS spectra prove the presence of EO in normal rat plasma and show (in this instance) that it circulates at the high end of the subnanomolar range as documented by prior RIA and bioassay methods.³

**References**


Supplementary Figure 1. Detection and Quantitation of Endogenous Ouabain in Rat Plasma by LC-MS-MS. A 10 ml of fresh rat plasma was extracted over C18 as described.1 Following reconstitution, an aliquot corresponding to only 0.25 ml of the original plasma was injected into a capillary C-18 column attached to a liquid chromatograph (Agilent 1100) interfaced with a Bruker Esquire Ion Trap Mass Spectrometer. A solvent gradient program was used to elute the bound materials which in turn were continuously monitored for positive ion species over an abbreviated scan range (400-650 m/z). In addition, selective ion monitoring was performed for positive ions equivalent to lithiated ouabain (i.e., m/z = 591.3). The top panel (red) shows the summed MS ion chromatogram for positive ions within the scanned range (i.e., 400-650 m/z). The second panel (green) shows the extracted MS ion current chromatogram for positively charged molecular ions with m/z = 591.3 (i.e., equivalent to lithiated EO). The third panel (blue) shows the extracted MS-MS ion current chromatogram resulting from the collision induced dissociation (CID) of all ions with 591.3 m/z. Note the prominent peak eluting at 27.9 minutes; the MS-MS spectrum of that ion peak is shown in the bottom panel (black). The targeted CID of the EO parent ion at m/z 591.3 led to formation of characteristic product ions at m/z 445.2, 427.2 and 409.2 (arrows) representing the lithiated aglycone of EO.
and its two dehydrated derivatives, respectively. Interpolation of the MS-MS ion current at 27.9 minutes with a standard calibration of the LC-MS-MS using ouabain under identical conditions (not shown) indicated that the EO content of the rat plasma sample was 141 pmoles/L. (Hamlyn and Manunta, unpublished).
Supplementary Figure 2. LC-MS-MS of Ouabain. Following analysis of the rat plasma sample in Supplementary Figure 1, ouabain (75 fmoles) was injected into the LC. The elution conditions, mass spectrometer settings, and ion monitoring conditions were identical to those used in Supplementary Figure 1. The top panel (red) shows the summed MS ion chromatogram for positively charged ions within the scanned range (i.e., 400-650 m/z). The second panel (green) shows the extracted MS ion current chromatogram for positively charged molecular ions with m/z = 591.3 (i.e., equivalent to lithiated ouabain). The third panel (blue) shows the extracted MS-MS ion current chromatogram resulting from the collision induced dissociation (CID) of ions with 591.3 m/z (the m/z of lithiated ouabain). A prominent ion current peak eluted at 27.9 minutes and the MS-MS spectrum of that ion peak shown in the bottom panel (black) reveals product ions at m/z 445.2, 427.2 and 409.2 (arrows) equivalent to the lithiated aglycone of ouabain and its singly and doubly dehydrated derivatives, respectively. (Hamlyn and Manunta, unpublished).
Supplementary Figure 3. Endogenous ouabain in human plasma determined by LC-MS-MS. A. LC-MS-MS of human plasma following LC separation and collision-induced dissociation of lithiated molecular ions at m/z 591 ± 0.5; the extracted ion current chromatogram for lithiated product ions was monitored at m/z 445.3. The prominent product ion current at 53 min corresponds with the elution of the EO aglycone, ouabagenin, following dissociation of EO. B. Mass spectrum of the product ions eluted at 53 min. The diamond at m/z 591 corresponds to the target ion (lithiated ouabain/EO). Product molecular ions at m/z 445.2, and 427.3 correspond to the lithiated aglycone of EO and its mono-dehydrated derivative, respectively.
Supplementary Figure 4. Immunoblots of aorta and bladder smooth muscle, and brain, membranes from wild type (C) and smooth muscle-specific $\alpha_2$ dominant negative ($\alpha_2^{SM/DN}$) mice (DN). An $\alpha_2$(1-120)Flag construct, the N-terminal 120 amino acid residues of the $\alpha_2$ Na$^+$ pump, under the control of a smooth muscle myosin heavy chain promoter, was expressed in the $\alpha_2^{SM/DN}$ mice. The construct expression was detected with anti-Flag antibodies in smooth muscle (bladder; insufficient aorta protein was available), but not in brain. The Na$^+$ pump $\alpha_2$ subunit (detected with anti-$\alpha_2$ HERED antibodies) was down-regulated in both smooth muscles, but not in brain. Lane protein content was controlled with $\alpha$-actin (Song, Chen, Kotlikoff and Blaustein, unpublished).