Overexpression of the Na⁺/K⁺ ATPase α2 But Not α1 Isoform Attenuates Pathological Cardiac Hypertrophy and Remodeling

Robert N. Correll,* Petra Eder,† Adam R. Burr, Sanda Despa, Jennifer Davis, Donald M. Bers, Jeffery D. Molkentin

Rationale: The Na⁺/K⁺ ATPase (NKA) directly regulates intracellular Na⁺ levels, which in turn indirectly regulates Ca²⁺ levels by proximally controlling flux through the Na⁺/Ca²⁺ exchanger (NCX1). Elevated Na⁺ levels have been reported during heart failure, which permits some degree of reverse-mode Ca²⁺ entry through NCX1, as well as less efficient Ca²⁺ clearance.

Objective: To determine whether maintaining lower intracellular Na⁺ levels by NKA overexpression in the heart would enhance forward-mode Ca²⁺ clearance and prevent reverse-mode Ca²⁺ entry through NCX1 to protect the heart.

Methods and Results: Cardiac-specific transgenic mice overexpressing either NKA-α1 or NKA-α2 were generated and subjected to pressure overload hypertrophic stimulation. We found that although increased expression of NKA-α1 had no protective effect, overexpression of NKA-α2 significantly decreased cardiac hypertrophy after pressure overload in mice at 2, 10, and 16 weeks of stimulation. Remarkably, total NKA protein expression and activity were not altered in either of these 2 transgenic models because increased expression of one isoform led to a concomitant decrease in the other endogenous isoform. NKA-α2 overexpression but not NKA-α1 led to significantly faster removal of bulk Ca²⁺ from the cytosol in a manner requiring NCX1 activity. Mechanistically, overexpressed NKA-α2 showed greater affinity for Na⁺ compared with NKA-α1, leading to more efficient clearance of this ion. Furthermore, overexpression of NKA-α2 but not NKA-α1 was coupled to a decrease in phospholemman expression and phosphorylation, which would favor greater NKA activity, NCX1 activity, and Ca²⁺ removal.

Conclusions: Our results suggest that the protective effect produced by increased expression of NKA-α2 on the heart after pressure overload is due to more efficient Ca²⁺ clearance because this isoform of NKA preferentially enhances NCX1 activity compared with NKA-α1. (Circ Res. 2014;114:249-256.)

Key Words: calcium signaling ■ hypertrophy ■ myocardial contraction ■ myocytes, cardiac ■ sodium

Years of study have made it clear that Na⁺ entry and exit pathways play an important role in the pathogenesis of heart disease because these systems are responsible not only for initiating the cardiac action potential (via voltage-gated Na⁺ channels), but also for closely regulating the influx and efflux of Ca²⁺ through the Na⁺/Ca²⁺ exchanger (NCX1). NCX1 is an electrogenic exchanger that removes 1 Ca²⁺ ion in exchange for internalizing 3 Na⁺ ions under normal conditions. However, the direction and rate of NCX1-mediated counter-transport are determined by membrane potential and relative concentrations of Na⁺ and Ca²⁺ inside and outside the myocyte. Multiple studies have indicated that intracellular Na⁺ concentration ([Na⁺]) is increased in numerous animal models of hypertrophy, as well as in human heart failure. This increased [Na⁺] during cardiac disease is likely an adaptive mechanism to reduce Ca²⁺ extrusion via NCX1 to augment contractility and cardiac function. However, this increase in cytosolic Ca²⁺ also increases the propensity for arrhythmias and may activate Ca²⁺-dependent signaling pathways involved in the hypertrophic program and apoptosis.

Numerous studies have characterized mechanisms by which [Na⁺] becomes elevated during cardiac disease, and they involve both entry and efflux pathways. Increased Na⁺ influx via both tetrodotoxin-sensitive Na⁺ channels and

The online-only Data Supplement is available with this article at http://circres.ahajournals.org/lookup/suppl/doi:10.1161/CIRCRESAHA.114.302293/-/DC1.

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Circulation Research is available at http://circres.ahajournals.org

DOI: 10.1161/CIRCRESAHA.114.302293
Na+/H+ exchanger has been demonstrated in a rabbit model of heart failure and in human heart failure. Overexpression of Na+/H+ exchanger in the murine heart resulted in increased [Na⁺], increased [Ca²⁺] (likely because of decreased Ca²⁺ exclusion by NCX1), heart failure and premature death accompanied by arrhythmia, increased nuclear factor of activated T cells (NFAT) translocation, and elevated Ca²+/calmodulin-dependent protein kinase II (CaMKII) activity, resulting in exclusion of histone deacetylase 4 from the nucleus. In addition, the late component of voltage-gated Na⁺ channel activity (Iₙaᵥ) is enhanced in some models of heart failure, whereas inhibition of Iₙaᵥ in CaMKII transgenic animals can improve diastolic function and eliminate premature arrhythmogenic contractions in papillary muscle preparations.

The Na⁺/K⁺ ATPase (NKA) is the primary Na⁺ extrusion pathway in cardiac myocytes, consuming ATP to pump 3 Na⁺ ions out in exchange for 2 K⁺ ions, which determines the driving force for Na⁺ entry into the myocyte. NKA is a heterodimer composed of an α subunit (α1 and α2 isoforms exist in the rodent heart) and β subunit (β1 is the only isoform in the heart) and is distributed both in the surface sarcolemma and in T-tubules. NKA is functionally coupled to NCX1 in cardiac myocytes where even small changes in NKA activity may alter the local [Na⁺] environment to modulate Ca²⁺ transients through NCX1. Accordingly, cardiac glycosides have been used for centuries to inhibit NKA activity, which during heart failure can blunt or reverse Ca²⁺ exit via NCX1 to enhance contractility. NKA activity is either downregulated or unchanged during heart failure and can be further modulated by phosphorylation of the endogenous regulator protein phospholemman (PLM), which, if hyperphosphorylated as shown in a rabbit model of heart failure enhances NKA activity. Alternatively, reduced phosphorylation of PLM as shown in human heart failure would lead to increased NKA inhibition.

The respective roles of the α1 and α2 subunits of NKA in the heart remain controversial. Early work suggested that α2 was directly coupled with NCX1 in T-tubules, whereas α1 regulated bulk Na⁺ levels in the cytosol. However, more recent work suggested that both isoforms are directly coupled to NCX1. Nevertheless, it seems that although the α1 subunit shows localization to both the surface sarcolemma and T-tubules, the α2 isoform is enriched as much as 5x more in T-tubules, suggesting that α2 may play a preferential role in the generation of signaling domains within T-tubules that modulate NCX1 function. Supporting this notion is a recent work demonstrating that partial inhibition of NKA-α2 but not NKA-α1 can increase Ca²⁺ transients, pointing to NKA-α2 as the isoform responsible for regulating NCX1 to control intracellular Ca²⁺ in the junctional space and subsequently affecting Ca²⁺ release from the sarcoplasmic reticulum (SR).

We generated transgenic mice with cardiac-specific overexpression of the α1 or α2 subunit of NKA to determine whether altered expression of an Na⁺ efflux protein could modulate the disease phenotype elicited by pressure overload in the heart. As suggested by previous reports, we demonstrate that a true overexpression of either α isoform is impossible because increased expression of one isoform results in compensatory downregulation of the other endogenous α isoform. However, increased expression of the α2 isoform, which effectively results in replacement of α1 with α2, attenuated the hypertrophic response after transverse aortic constriction (TAC) and was associated with faster Ca²⁺ extrusion via NCX1. In addition, the protective effect of α2 overexpression is not mimicked by α1 overexpression, positioning NKA-α2 as the more important isoform affecting Ca²⁺ removal by NCX1 during disease.

**Methods**

cDNAs encoding rat NKA-α1 and ouabain-resistant rat NKA-α2 (gift from Dr Jerry Lingrel, University of Cincinnati) were cloned into the murine α-myosin heavy chain promoter expression vector and used to inject newly fertilized oocytes to generate transgenic mice (FVB/N background). NFAT-luciferase transgenic mice were previously described. For cardiac pressure overload induction, mice aged 8 to 11 weeks were subjected to TAC or a sham surgical procedure, as previously described. Mouse ventricular cardiomyocytes were isolated as previously described. For Na⁺ measurements, isolated myocytes were plated on laminin-coated coverslips and loaded with 10 μmol/L 1,3-benzenedicarboxylic acid, 4,4′-[1,4,10-trioxa-7,13-diazacyclopentadecane-7,13-diylbis(5-methoxy-6,12-benzofurandiyl][bis[acetyloxy]methyl] ester (SBFI-AM) for 90 to 120 minutes (Invitrogen), as previously described. NKA activity was determined using an enzyme-linked assay measuring the rate of ADP production as linked to the rate of NADH fluorescence decrease in the absence or presence of 10 mmol/L strophanthidin (Sigma Aldrich), as previously described. Results are presented in all cases as mean±SEM. Values of P<0.05 were considered significant. See Online Data Supplement for expanded Materials and Methods.

**Results**

**Overexpression of NKA α2 But Not α1 Reduces Hypertrophy After TAC**

To determine the relative contribution of the α1 versus the α2 NKA isoform in the regulation of cytosolic Na⁺ levels and cardiac hypertrophy during disease, we created transgenic mice overexpressing each isoform using the α-myosin heavy chain promoter (Figures 1A and 2A). We obtained 1 line of NKA-α2 transgenic mice that showed 3-fold overexpression of protein in the heart relative to wild-type (Wt) levels (Figure 1B). Echocardiographic, gravimetric, and histological analyses showed no baseline phenotype in NKA-α2 transgenic mice with aging nor was survival affected (data not shown; Online Figure I). We next performed TAC surgery to induce pressure overload hypertrophy. After 2 weeks of TAC stimulation, hearts from the NKA-α2 transgenic animals showed a significant reduction in ventricular weight normalized to body weight compared with Wt controls subjected to TAC (Figure 1C; Online Figure II), which became even more...
apparent 10 weeks after TAC stimulation (Figure 1D). This reduction in cardiac hypertrophy in the transgenic mice after TAC correlated with reduced myocyte cross-sectional area (Figure 1E), reduced lung weight normalized to body weight (Figure 1F), a trend toward reduced mRNA expression of the hypertrophic marker atrial natriuretic factor, and a significant reduction in mRNA expression of brain natriuretic peptide (BNP), and β-myosin heavy chain (β-MHC) measured via quantitative polymerase chain reaction from Wt and NKA-α2 transgenic hearts after 10 weeks of TAC or sham surgery. Wt controls were analyzed after 10 to 12 weeks of sham surgery. For each experiment, number of mice analyzed is given within the graph. *P<0.05 vs sham; #P<0.05 vs Wt TAC.

**Total NKA Protein Levels Are Conserved During Subtype Overexpression**

Previous work has suggested that a change in the expression of a particular NKA isoform is balanced by altered expression of the other such that a constant level of NKA protein is maintained.21,24 In agreement with these previous observations, our Western blot experiments from whole-cell extracts of NKA-α1, NKA-α2, and Wt hearts demonstrated that overexpression of one NKA isoform elicited downregulation of the other isoform in a manner that preserved total levels of NKA (Figure 4A). Consistent with these observations, measurement of total ATPase activity in cardiac lysates from NKA-α2 transgenic and Wt hearts did not differ (Figure 4B). Although other investigators have suggested a somewhat different subcellular localization of NKA-α2 versus NKA-α1,22,29 it has been previously reported that both isoforms are expressed at the surface sarcolemma and T-tubules. Our findings agree with this because we were unable to see a difference in NKA localization when comparing myocytes from each transgenic line by confocal microscopy (Figure 4C). We also failed to observe any differences in localization of endogenous NKA-α1 versus NKA-α2 from isolated adult rat myocytes stained with the appropriate antibodies because both protein isoforms populated the sarcolemma and T-tubule at what seemed to be the same relative ratios (data not shown).

**NKA Overexpression Does Not Alter Na⁺/K⁺ Content But Modulates Ca²⁺ Efflux via an NCX1-Dependent Mechanism**

To determine the mechanism whereby NKA-α2 overexpression reduced cardiac hypertrophy and negative remodeling after TAC, we examined whether increased expression of either NKA isoform could alter Ca²⁺ handling. NKA is known to co-localize with NCX1, and several studies (and our unpublished work) have demonstrated coimmunoprecipitation,13 suggesting that NKA and NCX1 can coassociate as part of a complex to extent of the hypertropic response and loss of ventricular function compared with Wt or NKA-α1 transgenic mice.
Figure 2. Na’/K’ ATPase (NKA)-α1 transgenic (TG) mice show the same cardiac hypertrophic response after pressure overload as wild-type (WT) mice. 

A, Schematic representation of the transgene used to drive NKA-α1 expression in the mouse heart.

B, Immunoblot for NKA-α1 protein from the hearts of WT animals and 2 transgenic lines. Line 21.4 (high line) expresses more NKA-α1 protein than line 20.4 (low line).

C and D, Ventricular weight (VW) to body weight (BW) ratios measured from WT and line 20.4 or line 21.4 NKA-α1 transgenic mice after 2 weeks of transverse aortic constriction (TAC) or sham surgery.

E, Ventricular weight to body weight ratios measured from WT and high-line NKA-α1 transgenic mice after 12 weeks of TAC or sham surgery.

F, Histological analysis of myocyte cross-sectional area using wheat germ agglutinin-tetramethylrhodamine-5-(and-6)-Isothiocyanate (5(6)TRITC) stain of heart histological sections from WT and high-line NKA-α1 transgenic mice after 12 weeks of TAC or sham surgery.

G-I, mRNA levels of atrial natriuretic factor (ANF), brain natriuretic peptide (BNP), and β-myosin heavy chain (β-MHC) measured via quantitative polymerase chain reaction from WT and high-line NKA-α1 transgenic hearts after 12 weeks of TAC or sham surgery. WT controls were analyzed after 10 to 12 weeks of sham surgery. For each experiment, number of mice analyzed is given within the graph. * P<0.05 vs sham; # P<0.05 vs WT TAC.

To examine the mechanism whereby NKA-α2 might be antihypertrophic, we more directly measured the effect of increased NKA-α2 on NCX1-mediated Ca2+ extrusion in isolated adult myocytes. We observed that the rate of [Ca2+]i decline after caffeine-mediated depletion of SR stores, which is the result of both NCX1 and sarco(endo)plasmic reticulum Ca2+ ATPase (SERCA2) activity, was significantly faster in adult myocytes from NKA-α2 transgenic animals compared with WT and WT control myocytes (no Ni2+), whereas inhibition of NCX1 by pretreatment with 10 mmol/L Ni2+ resulted in a slower [Ca2+]i decay that was almost entirely reflective of SERCA2 activity and was not significantly different among the 3 groups (Figure 5E). These results suggest that NCX1

Figure 3. Na’/K’ ATPase (NKA)-α2 transgenic (TG) mice are protected from hypertrophy after 16 weeks of pressure overload. Ventricular weight (VW) to body weight (BW) ratio (A) and echocardiographic assessment of fractional shortening (FS%); B) in wild-type (WT), high-line NKA-α1 transgenic, or NKA-α2 transgenic mice after 16 weeks of transverse aortic constriction (TAC) surgery or from 24-week-old baseline controls.

C, Representative hematoxylin and eosin (H&E) and Masson trichrome–stained histological sections from hearts of WT, high-line NKA-α1 transgenic, or NKA-α2 transgenic mice after 16 weeks of TAC surgery. Cardiac histology from corresponding baseline control animals is shown in Online Figure I.

Compensation between Na’/K’ ATPase (NKA)-α1 and NKA-α2 in vivo or transgenic (TG) mice. 

A, Immunoblot for NKA-α1, NKA-α2, total NKA, and GAPDH protein from wild-type (WT) and transgenic heart homogenates. The asterisks show the lanes with reduced NKA protein expression because of compensation.

B, NKA activity measured as strophanthidin-sensitive ATP turnover rate in crude homogenates from WT and NKA-α2 transgenic hearts.

C, Subcellular localization of NKA-α1 and NKA-α2 protein in NKA-α1- or NKA-α2-isolated transgenic myocytes, respectively, via immunofluorescence and confocal microscopy.

Figure 4. Compensation between Na’/K’ ATPase (NKA)-α1 and NKA-α2 in vivo or transgenic (TG) mice. 

A, Immunoblot for NKA-α1, NKA-α2, total NKA, and GAPDH protein from wild-type (WT) and transgenic heart homogenates. The asterisks show the lanes with reduced NKA protein expression because of compensation.

B, NKA activity measured as strophanthidin-sensitive ATP turnover rate in crude homogenates from WT and NKA-α2 transgenic hearts.

C, Subcellular localization of NKA-α1 and NKA-α2 protein in NKA-α1- or NKA-α2-isolated transgenic myocytes, respectively, via immunofluorescence and confocal microscopy.
activity is responsible for the increased rate of Ca\(^{2+}\) extrusion in NKA-\(\alpha\)2-overexpressing adult myocytes, whereas NKA-\(\alpha\)1 does not seem to have this effect. This enhanced profile of NCX1 activity coupled to NKA-\(\alpha\)2 could be protective and possibly antihypertrophic if it more effectively reduced intracellular Ca\(^{2+}\) or some aspect of its global signaling because of rate of removal during relaxation (see Discussion section).

**NKA-\(\alpha\)2 Overexpression Does Not Alter Hypertrophic Signaling Pathways But Does Alter Rate of Na\(^{+}\) Removal**

Given that overexpression of Na\(^{+}/\)K\(^{-}\) ATPase (NKA)-\(\alpha\)1 and NKA-\(\alpha\)2 transgenic (TG) mice. A, Mean amplitude of Ca\(^{2+}\) transients measured from wild-type (Wt), NKA-\(\alpha\)2, and high-line NKA-\(\alpha\)-isolated transgenic cardiomyocytes paced at 0.5 Hz. B, Sarcoplasmic reticulum (SR) Ca\(^{2+}\) load measured from Wt, NKA-\(\alpha\)2, and high-line NKA-\(\alpha\)1-isolated transgenic cardiomyocytes via caffeine-induced Ca\(^{2+}\) release. C and D, [Na\(^{+}\)] measured from Wt, NKA-\(\alpha\)2, and high-line NKA-\(\alpha\)-isolated transgenic cardiomyocytes under resting conditions (C) and during stimulation at 2 Hz (D). Number of myocytes analyzed is given within the graph. P<0.05 vs WT. E, Rate of [Ca\(^{2+}\)]\(_{\text{in}}\) decline after caffeine-induced depletion of SR stores measured from Wt, NKA-\(\alpha\)2, and NKA-\(\alpha\)1 transgenic myocytes either in the presence of 10 mmol/L NiCl\(_{2}\) (to block Na\(^{+}/\)Ca\(^{2+}\) exchanger) or in the absence of NiCl\(_{2}\) (None). P<0.05 vs control (no nickel); P<0.05 vs WT of same treatment. F, Immunoblots of phosphoprotein and total protein levels for the indicated Ca\(^{2+}\)- and Na\(^{+}\)-handling proteins from cardiac homogenates of Wt, high-line NKA-\(\alpha\)-transgenic, or NKA-\(\alpha\)2 transgenic hearts after 16 weeks of transverse aortic constriction (TAC) or sham surgery. For each experiment, the number of mice analyzed is given in the graph. Quantification of the data is shown in Online Figure IV. P<0.05 vs sham; #P<0.05 vs WT TAC. PLM indicates phospholemman; PLN, phospholamban; RyR2, ryanodine receptor 2; and SERCA2, sarco(endo)plasmic reticulum Ca\(^{2+}\) ATPase 2.

**NKA-\(\alpha\)2 Isoform Has Greater Na\(^{+}\) Affinity and Pump Activity**

As demonstrated in Figure 5E, expression and phosphorylation of proteins such as PLN and PLM, which are important for controlling Na\(^{+}\) and Ca\(^{2+}\) handling, are altered in NKA-\(\alpha\)2 transgenic mice. To determine whether NKA-\(\alpha\)2 and NKA-\(\alpha\)1 functioned similarly in an uncompensated system, we carefully analyzed NKA activity in adult myocytes in which we overexpressed either the \(\alpha\)1 or \(\alpha\)2 isoform using adenoviral gene transfer (or a control \(\beta\)-galactosidase–expressing virus), followed by analysis of Na\(^{+}\) pump activity as a function of [Na\(^{+}\)].
Using an antibody that recognizes both NKA-α1 and NKA-α2, overexpression between the 2 isoforms was equivalent in total protein levels achieved after adenoviral infection (data not shown). The data show that NKA-α2–overexpressing myocytes had significantly greater affinity for Na+ and a higher rate of activity compared with endogenous activity in control-infected myocytes (Figure 6A–6C). These results suggest that the NKA-α2 isoform, which may be less regulated by PLM (see Discussion section), is more effective than NKA-α1 in pumping Na+ when expressed at high levels and should be more likely to maintain efficient forward-mode NCX1 activity during cardiac disease states, which we hypothesize would be cardioprotective (see Discussion section).

**Discussion**

Removal of Na+ from the cytosol of a cardiac myocyte is primarily accomplished through NKA-α1, which accounts for 88% of the NKA activity in the heart, whereas NKA-α2 accounts for the remaining 12%. Although these proteins share >85% identity, published reports suggest that they are not completely redundant and likely have specialized functions. NKA-α2 heterozygous gene-deleted mice are hypercontractile for cardiac function, whereas NKA-α1 heterozygous gene-deleted mice are hypocontractile. Although the reason for the profound phenotypic difference between these 2 heterozygous mouse models remains a mystery, especially because more recent studies suggest that both isoforms similarly interact with NCX1, the ultimate mechanism may relate to the observations we have made here: that NKA has greater affinity and pump activity for Na+ and that PLM levels are specifically reduced in NKA-α2–overexpressing hearts, effects that would tend to maintain proper Ca2+ handling in the face of disease insults. For example, transgenic mice expressing a mutant form of SERCA2 in the heart with greater Ca2+ affinity were protected from cardiac hypertrophy after TAC stimulation, presumably by better maintaining Ca2+ homeostasis during disease that would otherwise tend to secondarily lead to negative influences on the heart (ie, increased neurohumoral drive).

Previous observations suggest that NKA-α1 and NKA-α2 differentially regulate cardiac contractility, and here we provide further evidence demonstrating that these 2 isoforms play fundamentally different roles in the heart, this time in relation to regulation of the cardiac hypertrophic response. NKA-α1 transgenic mice showed a normal hypertrophic response after TAC surgery, whereas NKA-α2 transgenic mice were consistently less hypertrophic with less cardiac remodeling and signs of heart failure. The mechanism whereby increased NKA-α2 elicits such protection is intriguing, especially because overexpression of either NKA-α1 or NKA-α2 similarly reduces the Ca2+ transient amplitude and SR Ca2+ load. To determine whether NKA isoforms had differential effects on NCX1 activity, we used NiCl2, a well-described inhibitor of the exchanger.

There was no difference in Ca2+ extrusion between control, NKA-α2, or NKA-α1 in the presence of Ni2+, suggesting no change in the rate of Ca2+ decay when NCX1 was inhibited, and Ca2+ removal was primarily because of SERCA2 activity. However, when NiCl2 was absent, the rate of Ca2+ decay was significantly increased in NKA-α2 but not significantly different in NKA-α1 transgenic myocytes after caffeine-mediated SR Ca2+ release (Figure 5E), suggesting that the rate of Ca2+ extrusion through NCX1 is more under the influence of NKA-α2.

We reasoned that NKA-α2 could generate a selective reduction in [Na+]i, that prevents the activation of prohypertrophic signaling pathways after TAC surgery by reducing resting [Ca2+2], in T-tubule microdomains, which cannot be currently measured. However, this hypothesis lacks an ultimate molecular effector because there was no reduction in NFAT-luciferase activity, calcineurin/calmodulin interaction, or total CaMKII activity (Ca2+ dependent or Ca2+ independent, data not shown). These results suggest that normal hypertrophic signaling pathways are not differentially affected (reduced) in NKA-α2 transgenic hearts and that the protection we observed was possibly associated with a preservation in Na+ and Ca2+ handling that would otherwise become dysregulated and lead to disease secondarily (ie, increased β-adrenergic drive that attempts to maintain contractile function). Despa et al recently published more supportive evidence that NKA-α2 may have a selective effect on cardiac Na+ and Ca2+ handling compared with NKA-α1. They showed that selective inhibition of NKA-α2 but not NKA-α1 could increase Ca2+ transients and fractional Ca2+ release from the SR, likely because of the sensitizing effect of increased cleft Ca2+ on ryanodine receptor 2. Our results may ultimately indicate that enhanced local Na+ and Ca2+ removal elicited by NKA-α2 expression could subtly blunt alterations in abundance, post-translational modification, and activity of proteins in the T-tubule/SR junctional space to work against remodeling of the E–C coupling process and at least partially improve cardiac function, even in the face of activated hypertrophic signaling pathways such as calcineurin/NFAT and CaMKII, and that has the effect of reducing cardiac hypertrophy after pressure overload.

Another profound change in NKA-α2 hearts was a dramatic reduction in PLM levels and phosphorylation. PLM is an inhibitor of NKA activity that functions in a manner analogous to PLN inhibition of SERCA2 such that it generally inhibits NKA activity. Thus, its reduction in NKA-α2 transgenic...
hearts would be predicted to lead to greater NKA activity, removing Na⁺ more efficiently. PLM phosphorylated at S68 also functions as an inhibitor of NCX1, and overexpression of a PLM phosphomimetic protein resulted in arrhythmia and heart disease associated with loss of NCX1 activity. Therefore, the reduced phosphorylation of PLM we observed in our NKA-α2 transgenic mice, as well as the total reduction in PLM, may further increase NCX1 activity and enhance Ca²⁺ removal even during disease states that might otherwise lead to reverse-mode Ca²⁺ influx because of intracellular elevations in Na⁺ (Online Figure V). Enhanced Ca²⁺ extrusion through NCX1 elicited by a steeper Na⁺ gradient and reduced PLM phosphorylation would, in effect, prime the heart with bolstered forward-mode activity before induction of pressure overload, contributing to a positive profile of inotropy and lusitropy that should be cardioprotective. For example, mice lacking the gene for PLN are hypercontractile with optimized Ca²⁺ cycling, and crossing these mice with other mouse models of heart failure prevented or rescued disease likely by diminishing secondary neurohumoral signaling that is typically associated with reduced cardiac output and defects in Ca²⁺ cycling. Similarly, as stated above, overexpression of a mutant form of SERCA2 that enhances Ca²⁺ cycling in the hearts of transgenic mice produced less cardiac hypertrophy with pressure overload stimulation. Reciprocally, ventricle-specific deletion of the gene encoding NCX1 resulted in increased fibrosis and arrhythmias at baseline and increased cardiac hypertrophy after pressure overload stimulation that resulted in the death of all animals within 3 weeks after surgery, a result that is consistent with less cardiac hypertrophy because of optimized NCX1 activity in our NKA-α2 transgenic mice. Thus, NKA-α2 overexpression could be cardioprotective, producing less pressure overload–induced hypertrophy simply by optimizing Ca²⁺ handling and cardiac contractile performance (less need for neuroendocrine drive).

In addition to optimizing cardiac contractile function, NKA-α2 enhancement could be cardioprotective by affecting one or more microdomains of Na⁺. For example, Na⁺ overload during ischemia results in damage to mitochondria and reduction in ATP production that can be ameliorated via inhibition of voltage-gated Na⁺ channels, Na⁺/H⁺ exchanger, and NCX1. A recent article by Liu and O’Rourke further demonstrated that in a guinea pig aortic constriction model of heart failure, elevated [Na⁺], results in decreased mitochondrial Ca²⁺ uptake, which the authors suggest can negatively affect mitochondrial energy production, diminish mitochondrial Ca²⁺ buffering, and reduce the ability of the cell to respond to reactive oxygen species. Thus, augmented NKA-α2 expression in transgenic hearts may provide protection after TAC solely through a reduction in local [Na⁺]. Our current data certainly strengthen the case that the NKA subtypes are not functionally redundant and further suggest that NKA-α2 controls Na⁺ with a more proximal influence on NCX1 activity, which positively regulates contractile parameters of the heart and imparts protection from pressure overload stimulation.

Sources of Funding

This work was supported by grants from the National Institutes of Health (to J.D. Molkentin and D.M. Bers). J.D. Molkentin was also supported by the Howard Hughes Medical Institute. P. Eder was supported by the Austrian Science Fund (FWF, award P2775-B12). R.N. Correll was supported by grant number F32HL097551 from the National Heart, Lung, and Blood Institute.

Disclosures

None.

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Intracellular Na+ concentration is increased in many models of heart failure. We show that increased NKA-α2 subunit expression and phosphorylation of the Ca2+-ATPase enhances Ca2+ removal via upregulation of forward-mode Na+/Ca2+ exchanger activity. In addition, increased NKA-α2 subunit expression reduces phosphorylemman inhibition of the cardiac Na+Ca2+ exchanger. Role of phosphorylation. J Biol Chem. 2006;281:7784–7792.

This study was designed to examine whether increased expression of NKA, the primary Na+ efflux pathway in cardiac myocytes, could prevent the increase in intracellular Na+ associated with heart disease and mitigate hypertrophic remodeling. Our results show that upregulation of this pathway is protective, and we provide new insights into the respective roles of the NKA isoforms during disease. We found that increased NKA-α2 (but not α1) expression reduced disease after pressure overload and enhanced Ca2+ removal via upregulation of forward-mode Na+/Ca2+ exchanger activity. In addition, increased NKA-α2 resulted in a profile that is predicted to more effectively remove Na+ from the myocyte, thus collectively providing a cardioprotective profile that resists dysregulation of Na+ and Ca2+ levels. These results reveal a unique role of the α2 subunit of NKA in mitigating cardiac hypertrophic remodeling during pressure overload.
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_Circ Res._ 2014;114:249-256; originally published online November 11, 2013; doi: 10.1161/CIRCRESAHA.114.302293

_Circulation Research_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/114/2/249

Data Supplement (unedited) at:
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**Transgenic mice**
cDNAs encoding rat NKA-α1 and NKA-α2 (gift from Dr. Jerry Lingrel, University of Cincinnati) were cloned into the murine α-myosin heavy chain (MHC) promoter expression vector and used to inject newly-fertilized oocytes to generate transgenic mice (FVB/N background was used for all mice). We observed no baseline phenotypes in these mice by approximately four months of age. NFAT-luciferase mice were previously described 1. Experiments involving animals were approved by the Institutional Animal Care and Use Committee of Cincinnati Children’s Hospital.

**Echocardiography and pressure overload induction**
Mice were anesthetized with 2% isoflurane by inhalation. Echocardiography was performed in M-mode using a Hewlett Packard SONOS 5500 instrument with a 15 MHz transducer. For pressure overload induction, mouse littermates aged 8-11 weeks were subjected to transverse aortic constriction (TAC) or a sham surgical procedure, as previously described 1. Doppler echocardiography was performed on mice subjected to TAC in order to determine pressure gradients across the aortic constriction. In Figure 1D, 12 out of 26 Wt mice survived 10 weeks of TAC (46% survival) and 14 out of 19 NKA-α2 mice survived 10 weeks of TAC (74% survival). In Figure 2E, 7 out of 8 Wt mice survived 12 weeks of TAC (88% survival) and 9 out of 14 NKA-α1 mice survived 12 weeks of TAC (64% survival).

**Western blotting, immunoprecipitation and mRNA analysis**
Immunoprecipitation and Western blotting of mouse heart homogenates was performed using antibodies against NKA-α1 (Millipore and Developmental Studies Hybridoma Bank), NKA-α2 (Millipore), total NKA (a5-s, Developmental Studies Hybridoma Bank), p-PLN S16 (Badrilla), p-PLN T17 (Badrilla), PLN (Pierce), p-RyR2 S2808 (Badrilla), p-RyR2 S2814 (Badrilla), RyR2 (Santa Cruz), CaV1.2 (Alomone), NCX1 (Swant Inc.), SERCA2 (Badrilla), p-PLM S63 (Abgent), p-PLM S68 (Abgent), PLM (Abcam), β-tubulin (Santa Cruz), GAPDH (Research Diagnostics Inc.), calcineurin B (Sigma-Aldrich) and calmodulin (Zymed Laboratories). Secondary antibodies for chemifluorescent detection were from Santa Cruz. Chemifluorescent detection was performed with the Vistra ECF reagent (Amersham Pharmacia Biotech). Secondary antibodies for fluorescent detection were from LI-COR and immunoblots were visualized using the Odyssey CLx imaging system (LI-COR). RNA was extracted from ventricles using the RNeasy Kit according to manufacturer’s instructions (Qiagen). Reverse transcription was performed using the SuperScript III First-Strand Synthesis System (Invitrogen). Analysis of the hypertrophic markers was performed using individual Taqman gene expression assays (Applied Biosystems). Messenger RNA expression was quantified, normalized to GAPDH, and expressed relative to control.

**Isolation of adult cardiomyocytes and Ca²⁺ measurements**
Adult mouse ventricular cardiomyocytes were isolated as previously described 2. Cardiac myocytes were loaded with 2 μM Fura-2 acetoxymethyl ester (Invitrogen) for 15 min in Tyrode solution containing: 131 mM NaCl, 4 mM KCl, 1 mM CaCl₂, 1 mM MgCl₂, 10 mM glucose, 10 mM HEPES (pH 7.4). The Fura-2 fluorescence ratio was determined using a Delta scan dual-beam spectrophotometer (Photon Technology International) operated at an emission wavelength of 510 nM and excitation wavelengths of 340 and 380 nM. The stimulation frequency for Ca²⁺ transient measurements was 0.5 Hz. For caffeine-induced Ca²⁺ release, cells were perfused with a control solution and stimulated at 0.5 Hz until stabilization of the transients. The electrical stimulation was interrupted and the cells were perfused for 1 min with either control solution or a solution containing 10 mM NiCl₂ to block NCX activity. 10 mM caffeine (dissolved in Tyrode solution) was added to induce Ca²⁺ store depletion. Baseline Ca²⁺ levels, transient amplitude, caffeine-induced Ca²⁺ release (estimated by the 340 nM/380 nM ratio), and Ca²⁺ decay kinetics were analysed using Felix 1.1 and Ion Wizard (IonOptix) software.

**[Na⁺]i measurements**
Isolated myocytes were plated on laminin-coated coverslips and loaded with 10 μM SBFI-AM for 90-120 min (Invitrogen) as previously described 3. SBFI was allowed to de-esterify for 20 min in Tyrode solution containing:
140 mM NaCl, 4 mM KCl, 1 mM CaCl₂, 1 mM MgCl₂, 10 mM glucose, 5 mM HEPES (pH 7.4). SBFI was alternately excited at 340 and 380 nm (F₃₄₀ and F₃₈₀) using an Optoscan monochromator (Cairn Research, Faversham, UK) and fluorescence was collected at 535±20 nm. F₃₄₀/F₃₈₀ was calculated after two background subtraction and converted to [Na⁺] by calibration at the end of each experiment in the presence of 10 μM gramicidin and 100 μM strophanthidin.

**Na⁺/K⁺ ATPase activity measurements in adult rat cardiac myocytes**

Adult rat cardiac myocytes were isolated and plated onto 22mm circular coverslips and infected with either NKA-α₁, NKA-α₂, or β-galactosidase-expressing adenovirus at 5 MOI. 24-34 hours post-infection, cardiac myocytes were loaded with 10 μM SBFI (Invitrogen) with 0.05% Pluronic F-127 (Sigma) in DMEM at room temperature for 45 minutes followed by two washes and 15 minutes of de-esterification in Tyrode solution containing: 140 mM NaCl, 4 mM KCl, 1 mM CaCl₂, 10 mM glucose, and 10 mM Hepes. Photometric measurements were performed on a Nikon Eclipse Ti-U inverted microscope. Cells were alternatively excited at 340nm and 380nm using a Delta Scan dual-beam spectrofluorophotometer (Photon Technology, Birmingham, NJ) at a rate of 1 Hz to avoid photo bleaching. Fluorescent emission was recorded by a CoolSnap ES2 camera connected to a computer running the EZ Ratio Pro software by PTI. An *in situ* NKA assay was performed as previously described. After a short baseline recording, cells were perfused with Na⁺ loading buffer that lacks K⁺, containing: 145 mM NaCl, 2 mM EGTA, 10 mM HEPES, and 10 mM glucose, which completely inhibits NKA and forces [Na⁺] to rise. After 30 minutes Na⁺ levels reached a steady maximal value and NKA was activated by perfusion of a solution containing 140 mM TEA, 4 mM KCl, 2 mM EGTA, 10 mM HEPES, and 10 mM glucose. Once Na⁺ returned to a stable minimum level, a calibration was performed as previously described. Solutions containing 0, 10, 20, 30, and 40 mM Na⁺ were derived from a combination of solutions made up of: 30 mM NaCl, 115 sodium gluconate, and a solution containing 30 mM KCl and 115 mM potassium gluconate. Calibration buffers also contained 10 μM gramicidin D, 100 μM strophanthidin, 10 mM glucose, and 2 mM EGTA. Regions of interest were drawn inside the boundaries of individual cardiac myocytes and background fluorescence was subtracted from each image before calculating the ratio of 340/380 nm. Ratios were converted to Na⁺ concentration by fitting a linear equation derived from the calibration experiments. A velocity of Na⁺ efflux was then determined for each concentration of Na⁺.

**NKA and NFAT activity assay**

Na⁺/K⁺ ATPase activity was determined using an enzyme-linked assay measuring the rate of ADP production as linked to the rate of NADH fluorescence decrease in the absence or presence of 10 mM strophanthidin (Sigma Aldrich), as previously described. Briefly, 2 μg of crude protein extract from heart homogenates was incubated for 20 min at 37°C in solution containing: 100 mM NaCl, 20 mM KCl, 8 mM MgCl₂, 40 mM Tris (pH 7.4), 1 mM EGTA, 25 mM choline chloride, 1 U/ml lactate dehydrogenase, 1 U/ml pyruvate kinase, 1 mM phosphoenolpyruvate, 80 μM NADH for a total reaction volume of 2.5 mL. The reaction was initiated with the addition of 1 mM ATP. NADH fluorescence was continuously monitored (excitation 340 nm, emission 460 nm) for 20 min using a spectrofluorimeter (PTI Delta Scan-1, Photon Technology International). Rates were calculated as μmoles ATP/minute/mg protein. NFAT activity assays were performed on heart homogenates as described previously.

**CaMKII activity assay**

CaMKII activity was determined using the SignaTect calcium/calmodulin-dependent protein kinase assay system (Promega) according to the manufacturer’s instructions. For the assay, homogenates were made from WT or NKA-α₂ hearts at baseline or after two weeks of TAC surgery using the following buffer: 10 mM Tris-HCl (pH 7.4), 150 mM NaCl, 1 mM dithothreitol, 20% glycerol, 0.1% Triton X-100, 1x protease inhibitor cocktail (Calbiochem); protein concentration was determined by Bradford assay and CaMKII activity was determined from 2 μg of protein.

**Histology and immunohistochemistry**

Analysis of cross-sectional areas was performed on histological sections from paraffin-embedded heart tissue. TRITC-conjugated wheat germ agglutinin (Sigma-Aldrich) was used to identify sarcolemmal membranes as described previously. Isolated cardiomyocytes plated on laminin and fixed with 4% paraformaldehyde were treated with NKA-α₂ (Millipore) or NKA-α₁ antibody (Developmental Studies Hybridoma Bank) and FITC-conjugated antibody (Invitrogen) to visualize protein localization.
Statistics
Results are presented in all cases as mean ± SEM. Statistical analysis was performed using Prism 5 (Graphpad Software) for unpaired two-tailed t-tests. P-values less than 0.05 were considered significant.

References
Online Figure I. Cardiac histological staining from baseline control mice. Representative H&E and Masson’s trichrome-stained histological sections from hearts of Wt, high-line NKA-α1 transgenic or NKA-α2 transgenic mice at 24 weeks of age to show the state of hearts from these transgenic lines, which was normal. Cardiac histology from TAC-operated mice is found in Figure 3C and showed no differences in the degree of fibrosis induction between the transgenic lines and the Wt.
Online Figure II. NKA-α2 but not NKA-α1 transgenic mice show less cardiac hypertrophy after pressure overload for 2 weeks. Comparison of ventricle weight to body weight ratios measured from Wt, NKA-α2 and high-line NKA-α1 transgenic mice 2 weeks after TAC or a sham surgery. For each experiment, number of mice analysed is given within the graph. *P<0.05 versus sham; #P<0.05 vs Wt TAC.
Online Figure III. NKAα2-mediated cardioprotection after pressure overload does not involve calcineurin/NFAT or CaMKII signalling. A, NFAT luciferase activity measured from NFAT-luciferase transgenic (control) and double NKAα2/NFAT-luciferase transgenic hearts after 2 weeks of TAC or a sham surgery. B, Immunoblots of calcineurin B and calmodulin (CaM) protein from calcineurin B immunoprecipitation fractions from Wt and NKAα2 heart homogenates after 2 weeks of TAC or a sham surgery. For each experiment, number of mice analysed is given within the graph. C, CaMKII activity measured from Wt and NKAα2 transgenic heart homogenates at baseline or after 2 weeks of TAC surgery. *P<0.05 versus sham. No significant differences observed between TAC treatments.
Online Figure IV. Quantification of cardiac protein expression after 16 week TAC surgery. Floating bar graph representation of immunoblots from the same samples as shown in Figure 5F. The data were normalized to β-tubulin or total PLM, PLN or RyR2 (for phosphoproteins). *P<0.05 vs sham of same genotype. #P<0.05 vs Wt TAC.
Online Figure V.

**WT and NKA-α1 overexpression**

- Standard Ca\(^{2+}\) and Na\(^{+}\) Removal
- Normal Hypertrophic Response

**NKA-α2 overexpression**

- Enhanced Ca\(^{2+}\) and Na\(^{+}\) Removal
- Resistant to Hypertropic Stimuli