Endothelial nitric oxide synthase decreases β-adrenergic responsiveness via inhibition of the L-type Ca\(^{2+}\) current

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Wang H, Kohr MJ, Wheeler DG, Ziolo MT: Endothelial nitric oxide synthase decreases β-adrenergic responsiveness via inhibition of the L-type Ca\(^{2+}\) current. Am J Physiol Heart Circ Physiol 294: H1473–H1480, 2008. First published January 18, 2008; doi:10.1152/ajpheart.01249.2007.—Signaling via endothelial nitric oxide synthase (NOS3) limits the heart’s response to β-adrenergic (β-AR) stimulation, which may be protective against arrhythmias. However, mechanistic data are limited. Therefore, we performed simultaneous measurements of action potential (AP), using patch clamp, Ca\(^{2+}\) transients (fluo 4), and myocyte shortening (edge detection). L-type Ca\(^{2+}\) current (\(I_{Ca}\)) was directly measured by the whole cell ruptured patch-clamp technique. Myocytes were isolated from wild-type (WT) and NOS3 knockout (NOS3\(^{-/-}\)) mice. NOS3\(^{-/-}\) myocytes exhibited a larger incidence of β-AR (isoproterenol, \(1 \mu M\))-induced early afterdepolarizations (EADs) and spontaneous activity (defined as aftercontractions). We also examined \(I_{Ca}\) in α and β AR, a major trigger for EADs. NOS3\(^{-/-}\) myocytes had a significantly larger β-AR-stimulated increase in \(I_{Ca}\) compared with WT myocytes. In addition, NOS3\(^{-/-}\) myocytes had a larger response to β-AR stimulation compared with WT myocytes in Ca\(^{2+}\) transient amplitude, shortening amplitude, and AP duration (APD). We observed similar effects with specific NOS3 inhibition [\(L-N^\epsilon-(1\text{-iminoethyl})\text{-ornithine} (L\text{-NIO}), 10 \mu M\)] in WT myocytes as with NOS3 knockout. Specifically, L-NIO further increased isoproterenol-stimulated EADs and aftercontractions. L-NIO also further increased the isoproterenol-stimulated \(I_{Ca}\), Ca\(^{2+}\) transient amplitude, shortening amplitude, and APD (all \(P < 0.05\) vs isoproterenol alone). L-NIO had no effect in NOS3\(^{-/-}\) myocytes. These results indicate that NOS3 signaling inhibits the β-AR response by reducing \(I_{Ca}\) and protects against arrhythmias. This mechanism may play an important role in heart failure, where arrhythmias are increased and NOS3 expression is decreased.

endothelial nitric oxide synthase; cardiac myocytes; early afterdepolarizations; action potential


Nitric oxide (NO), produced via NO synthase (NOS), is also an important regulator of cardiac contractility (54). Cardiac myocytes constitutively express neuronal NOS (nNOS, NOS1) and endothelial NOS (eNOS, NOS3). Recent studies have shown that NOS1 and NOS3 differentially regulate the response to β-AR stimulation (4). NOS1 signaling has been found to potentiate the response to β-AR stimulation (4). The observed effects of NOS3 signaling on the β-AR response are the opposite of NOS1 (30), that is, studies have shown that NOS3 signaling depresses the functional response to β-AR stimulation. For example, mice with specific knockout of NOS3 (NOS3\(^{-/-}\)) have an increased response to β-AR stimulation (4, 11, 19, 20, 47). Similarly, transgenic mice with cardiac myocyte-specific NOS3 overexpression have a decreased response to β-AR stimulation (9, 23). Although the vast majority of studies found the above effects, it should be noted that a few studies observed dissimilar results (29, 46). In addition, there are limited studies investigating the mechanism of the NOS3-induced reduction of the β-AR response.

The regulation of β-AR stimulation by NOS3 may be via modulation of the L-type Ca\(^{2+}\) channel, since one study has shown that nonspecific NOS inhibition can further increase the cAMP-stimulated L-type Ca\(^{2+}\) current (\(I_{Ca}\)) (33). However, specific NOS isoforms were not examined in this study. Exogenous NO (i.e., NO donors) has also been found to decrease β-AR-stimulated \(I_{Ca}\) (48). NOS3 is localized to the caveolae, along with the L-type Ca\(^{2+}\) channel and the B2-AR receptor (3, 17). In addition, a study showed that myocytes from female mouse hearts have smaller β-AR -induced \(I_{Ca}\) and a higher association between NOS3 and caveolin-3 compared with myocytes from male mouse hearts (43). Indirect evidence also suggests that NOS3 can regulate \(I_{Ca}\) via activation of the β3-AR receptor (4, 47, 53). These studies have led groups to hypothesize that NOS3 regulates \(I_{Ca}\) (4, 28, 43). However, this has yet to be observed in NOS3\(^{-/-}\) myocytes (21, 46).

High sympathetic activation and specifically increased \(I_{Ca}\) can be detrimental to cardiac myocytes, leading to arrhythmias (24). Interestingly, transgenic mice overexpressing NOS3 demonstrated a lower incidence of spontaneous arrhythmic contractions in cultured neonatal myocytes (32). In addition, NOS3\(^{-/-}\) mice had a higher incidence of arrhythmias (28, 39). However, the mechanism of the antiarrhythmic effect of NOS3 is unknown. The regulation of \(I_{Ca}\) by NOS3 would also affect the action potential (AP) waveform, and AP prolongation may play a role in reentrant arrhythmias (37). There are no studies that we are aware of examining the AP waveform in isolated myocytes from NOS3\(^{-/-}\) mice. Therefore, the purpose of this study is to examine the effects of NOS3 knockout or acute inhibition on AP, Ca\(^{2+}\) transients, and myocyte shortening. We also measured \(I_{Ca}\). We hypothesize that NO produced via NOS3 is protective against arrhythmias (defined as early
afterdepolarizations and aftercontractions) by modulation of the β-AR-stimulated \( I_{Ca} \). This reduction in \( I_{Ca} \) will also result in a decrease in action potential duration (APD) measured as time to 90% repolarization (APD90), \( Ca^{2+} \) transients, and myocyte shortening amplitude.

**Materials and Methods**

**Isolation of ventricular myocytes.** Ventricular myocytes were isolated from NOS3−/− mice (42, 52; Jackson Laboratories, Bar Harbor, ME) and corresponding wild-type (WT) mice (C57BL/6J) as previously described (27). Briefly, the heart was mounted on a Langendorff apparatus and perfused with modified MEM (37°C, bubbled with 95% \( O_2 \)-5% \( CO_2 \); Sigma, St. Louis, MO). Blendedzine type IV (0.077 mg/ml; Roche Applied Science, Indianapolis, IN) was then added to the perfusate. After 10–15 min, the heart was taken down, the ventricles were minced, and myocytes were dissociated by trituration. Subsequently, the myocytes were filtered, centrifuged, and resuspended in MEM containing 200 \( \mu \)M \( Ca^{2+} \). Myocytes were used within 6 h after isolation. All animal protocols and procedures were performed in accordance with National Institutes of Health guidelines and approved by the Institutional Laboratory Animal Care and Use Committee at The Ohio State University.

**Measurement of \( I_{Ca} \).** Whole cell voltage-clamp was used to measure \( I_{Ca} \) using an Axopatch-200B amplifier and pClamp 8.1 software (Axon Instrument, Foster City, CA), as described previously (56). Electrodes (borosilicate glass tubing), with a resistance of 1.5–3 MΩ, were filled with (in mM): 120 CsCl, 6 MgCl₂, 10 EGTA, 10 HEPES, and 2 MgATP, pH 7.2 adjusted with CsOH. The bath solution consisted of (in mM): 120 NaCl, 4 CsCl, 1 MgCl₂, 1 CaCl₂, 10 glucose, 5 HEPES, and 1 l-arginine, pH 7.4 adjusted with CsOH or HCl. \( I_{Ca} \) was elicted by 200-nseg pulses to 0 mV from a holding potential of ~80 mV (following a prepulse to ~40 mV) at a frequency of 0.2 Hz. This procedure isolates the \( I_{Ca} \) by inactivation of the Na⁺ current with the prepulse, and replacement of K⁺ with \( Cs^{+} \) eliminates the K⁺ current. Measurements were performed at room temperature.

**Simultaneous measurement of \( Ca^{2+} \) transients, cell shortening, and AP.** Myocytes were loaded at 22°C with fluo 4-AM (10 \( \mu \)M; Molecular Probes, Eugene, OR) for 30 min and washed out, and then 30 min were allowed for intracellular deesterification. The instrumentation used for cell fluorescence measurement was a Cairn Research system (Crescent Electronics, Sandy, UT). Data were expressed as means ± SE. Differences between multiple groups were evaluated for statistical significance using an ANOVA (followed by Neuman-Keuls test) or by paired or unpaired Student’s t-test for two groups. Statistical significance was accepted at the level of \( P < 0.05 \).

**Results**

**NOS3 and arrhythmogenesis.** Previous studies have shown that NOS3 knockout leads to increased arrhythmias in ouabain-treated myocytes or with digoxin in vivo (28, 39). Thus we investigated if NOS3 knockout or inhibition increases the β-AR-stimulated arrhythmogenesis at the level of the myocyte. Figure 1 shows representative examples, in the presence of β-AR stimulation (ISO, 1 \( \mu \)M), of early afterdepolarizations (EADs) in NOS3−/− and WT myocytes with NOS3 inhibition (l-NIO, 10 \( \mu \)M) (Fig. 1A). Summary data are shown in Fig. 1B. No EADs were observed in WT or NOS3−/− myocytes during control (basal) stimulation. In the presence of ISO (1 \( \mu \)M), 57 ± 12% of NOS3−/− myocytes per heart vs. only 8 ± 5% \( P < 0.05 \) vs NOS3−/−) of WT myocytes per heart displayed EADs. Acute inhibition of NOS3, in the presence of ISO, increased the incidence of EADs in WT myocytes per heart (37 ± 11%, \( P < 0.05 \) vs. ISO alone). Spontaneous activity (defined as aftercontractions, ACs) was also observed in NOS3−/− myocytes during β-AR stimulation (Fig. 1C). Summary data are shown in Fig. 1D. No ACs were observed in WT or NOS3−/− myocytes during basal stimulation. However, during β-AR stimulation, 69 ± 10% of NOS3−/− myocytes per heart vs. only 6 ± 6% \( P < 0.05 \) vs NOS3−/−) of WT myocytes per heart had ACs. Acute inhibition of NOS3, in the presence of ISO, increased the incidence of ACs in WT myocytes per heart (35 ± 9%, \( P < 0.05 \) vs. ISO alone). During β-AR stimulation, we observed EADs and ACs in myocytes isolated from all NOS3−/− hearts (100%), whereas myocytes from only 25% of WT hearts exhibited spontaneous activity. These data suggest that NOS3 signaling can protect cardiac myocytes from β-AR-stimulated arrhythmias.

**Effects of NOS3 on \( I_{Ca} \).** Abnormal L-type \( Ca^{2+} \) channel activity can cause EADs (24). Thus we examined the effects of NOS3 signaling on the \( I_{Ca} \) in myocytes from WT and NOS3−/− mice. Our data showed that there was no statistical difference in basal \( I_{Ca} \) between the two groups (WT: 3.5 ± 0.2 pA/pF, NOS3−/−: 3.8 ± 0.4 pA/pF). Figure 2, A and B, shows representative current traces and time plots of the effects of β-AR stimulation (ISO, 1 \( \mu \)M) and NOS3 inhibition (l-NIO) in a WT myocyte and a NOS3−/− myocyte. Figure 2C shows NOS3−/− myocytes had a significantly larger response to β-AR stimulation compared with WT (increased 88 ± 10% of control in NOS3−/− vs. 58 ± 7% of control in WT, \( P < 0.05 \)). In addition, specific NOS3 inhibition with l-NIO, in the presence of ISO, further increased \( I_{Ca} \) in WT myocytes (26 ± 12% from ISO alone) but had no effect in NOS3−/− myocytes (decreased 7 ± 3% from ISO alone, \( P < 0.05 \) vs. WT; Fig. 2D). This small decrease was most likely due to the rundown of \( Ca^{2+} \) current. These data indicate that the L-type \( Ca^{2+} \) channel is an important target of NOS3 and are consistent with a NOS3-mediated reduction in \( I_{Ca} \) being protective against arrhythmias.

**Effects of NOS3-derived NO on myocyte function.** We also tested the effects of NOS3 on myocyte function. Functional experiments were performed on isolated myocytes from...
NOS3−/− and WT mice in which AP, Ca2+ transients, and shortening were simultaneously measured at a stimulation frequency of 1 Hz. Representative examples of AP (top), myocyte shortening (middle), and Ca2+ transient (bottom) traces from a WT and NOS3−/− myocyte are shown in Fig. 3 and summarized in Figs. 4 and 5.

After reaching steady state, the myocytes were perfused with ISO (1 μM). In WT myocytes, β-AR stimulation increased APD, measured as time to 90% repolarization (APD90) (49 ± 9 vs. 72 ± 10 ms), shortening amplitude (1.2 ± 0.1 vs. 7 ± 2 μm), and Ca2+ transient amplitude (0.34 ± 0.04 vs. 1.3 ± 0.1 ΔF/F0) and hastened the rate of Ca2+ decline, measured as time to 50% relaxation (RT50) (267 ± 20 vs. 147 ± 8 ms) (all P < 0.05 vs. control). In NOS3−/− myocytes, ISO also increased APD90 (49 ± 12 vs. 119 ± 12 ms), shortening amplitude (2.6 ± 0.6 vs. 14 ± 2 μm), and Ca2+ transient amplitude (0.5 ± 0.1 vs. 1.9 ± 0.3 ΔF/F0) and hastened the rate of Ca2+ decline (Ca2+ transient RT50: 276 ± 39 vs. 124 ± 7 ms; all P < 0.05 vs. control). However, there was a larger response to β-AR stimulation in myocytes from NOS3−/− compared with WT mice in APD90 (P < 0.05), shortening amplitude (P < 0.05), and a trend in Ca2+ transient amplitude (P = 0.06). These data suggest that myocytes from NOS3−/− mice have a larger response to β-AR stimulation compared with WT myocytes.
After steady state, the bath solution was switched to ISO (1 μM) plus l-NIO (10 μM), selective NOS3 inhibitor, in a WT (A) and NOS3−/− (B) myocyte. C: summary data (means ± SE) of the effects of ISO in WT and NOS3−/− myocytes. D: summary data (means ± SE) of the effects of l-NIO in WT and NOS3−/− myocytes. *P < 0.05 vs. WT (n = 5 hearts for WT; n = 5 hearts for NOS3−/−).

Fig. 2. A and B: representative traces (top) and time plot (bottom) of ICa with ISO (1 μM) and l-NIO (10 μM), selective NOS3 inhibitor, in a WT (A) and NOS3−/− (B) myocyte. C: summary data (means ± SE) of the effects of ISO in WT and NOS3−/− myocytes. D: summary data (means ± SE) of the effects of l-NIO in WT and NOS3−/− myocytes. *P < 0.05 vs. WT (n = 5 hearts for WT; n = 5 hearts for NOS3−/−).

DISCUSSION

It is known that NOS3 signaling leads to antiadrenergic effects and is protective against arrhythmias. However, the mechanism(s) of this effect is unknown. Spontaneous activity (EADs and aftercontractions) in our study was observed at the level of NOS3−/− myocytes (NOS3 gene deficiency was confirmed by Western Blot, data not shown) or with acute NOS3 inhibition in WT myocytes. We also investigated ICa in NOS3−/− myocytes. We are the first to report that NOS3−/− myocytes have an increased ICa in response to β-AR stimulation. We further demonstrated that acute NOS3 inhibition in WT myocytes also caused a further increase in the β-AR-stimulated ICa. We simultaneously measured AP, Ca2+ transients, and myocyte shortening. We observed that NOS3−/− myocytes had a significantly prolonged APD, increased myocyte shortening, and a trend toward increased Ca2+ transient amplitude with β-AR stimulation compared with WT myocytes. These same results were observed with acute NOS3 inhibition in WT myocytes (i.e., significantly prolonged APD, increased Ca2+ transient amplitude, and myocyte shortening). Therefore, it is likely that NOS3 signaling modulates ICa to limit the β-AR response and protect against arrhythmias.
NOS3 and arrhythmogenesis. Previous studies have observed that NOS3−/− mice have an increased incidence of arrhythmias. This was observed as increased ouabain-induced aftercontractions in isolated NOS3−/− myocytes due to an increase in a transient inward current (most likely Na+/Ca2+ exchanger) (28). Similar effects were demonstrated in a study observing electrocardiograms in NOS3−/− and WT mice. Digoxin induced more premature ventricular beats and ventricular tachycardia in the NOS3−/− mice (39). These premature ventricular beats are analogous to the afterdepolarizations observed in their isolated myocyte studies. Our data show that myocytes with NOS3 knockout or acute NOS3 inhibition had an increased incidence of EADs and aftercontractions in response to β-AR stimulation (Fig. 1). Previous work has shown that EADs can result from abnormal I\textsubscript{Ca} activity (24). In addition to EADs, increased Ca\textsuperscript{2+} influx via I\textsubscript{Ca} can also lead to aftercontractions. This increased Ca\textsuperscript{2+} influx can lead to SR Ca\textsuperscript{2+} overload and spontaneous release, resulting in aftercontractions (45). Therefore, NOS3 signaling is protective against arrhythmias by inhibiting β-AR-stimulated I\textsubscript{Ca}.

NOS3 and the IC\textsubscript{a}. Studies have shown that EADs can be induced using the L-type Ca\textsuperscript{2+} channel agonist BAY K 8644 (15, 24). Additionally, studies have shown that L-type Ca\textsuperscript{2+} channel antagonists can significantly decrease the occurrence of EADs (24, 44). Exogenous NO (i.e., NO donors) and nonspecific NOS inhibitors have also been shown to regulate β-AR-stimulated I\textsubscript{Ca} (33, 48), and it was hypothesized that this effect was via NOS3. Within cardiac myocytes, NOS3 is localized with the L-type Ca\textsuperscript{2+} channel and the β2-AR receptor to the caveolae (3, 17). However, studies investigating β-AR-stimulated I\textsubscript{Ca} in NOS3−/− myocytes observed no difference compared with WT myocytes (21, 46). We observed an in-
crease in the β-AR-stimulated \( I_{Ca} \) from NOS3\(^{-/-}\) myocytes compared with WT myocytes (Fig. 2). We also observed that acute NOS3 inhibition in WT myocytes further increased the β-AR-stimulated \( I_{Ca} \) (Fig. 2). Thus our data demonstrate that NOS3 is able to modulate the β-AR-stimulated \( I_{Ca} \). We believe that the inability of previous studies to observe a difference in the β-AR-stimulated \( I_{Ca} \) in NOS3\(^{-/-}\) myocytes was due to the lack of l-arginine (precursor of NO) in the solutions they used. We (55) and others (40) have found for endogenous NO to affect \( I_{Ca} \), measured using the ruptured patch-clamp technique, l-arginine must be added to the solution. Additionally, we did not observe a difference in basal \( I_{Ca} \) between NOS3\(^{-/-}\) and WT myocytes, suggesting that NOS3 specifically modulates the β-AR-stimulated \( I_{Ca} \). Thus the NOS3-mediated reduction in β-AR-stimulated \( I_{Ca} \) will reduce the incidence of EADs and aftercontractions and protect the heart from arrhythmias.

In cardiac myocytes, NOS3 is localized in the caveolae with superoxide dismutase (SOD; see Refs. 8 and 17), a superoxide scavenger that which will prevent \( O_2^- \) from reacting with NO. Thus NO generated from NOS3 is more likely to activate guanylate cyclase and subsequently form cGMP. The cGMP pathway in cardiac myocytes is primarily via activation of the cGMP-dependent protein kinase (PKG) (49). Previous work has shown that exogenous NO (48), cGMP analogs (26) or exogenous PKG (34) can decrease the effects of ISO (1, P and shortening amplitude. *P < 0.05 vs. WT ISO; n = 8 hearts for WT, n = 5 hearts for NOS3\(^{-/-}\.

![Graph of Ca\(^{2+}\) Transient Amplitude](image1)

**Graph of Ca\(^{2+}\) Transient Amplitude**

**Graph of Shortening Amplitude**

Fig. 5. Summary data (means ± SE) of the effects of ISO (1 μM) and l-NIO (10 μM), a selective NOS3 inhibitor, on Ca\(^{2+}\) transients and shortening amplitude. *P < 0.05 vs. WT ISO; n = 8 hearts for WT, n = 5 hearts for NOS3\(^{-/-}\.

- ARG-stimulated \( I_{Ca} \) could potentially be inhibiting a K\(^{+}\) current that would result in a prolonged APD. It is known that prolonged APD is a contributing factor to reentrant arrhythmias (38). Thus NOS3 signaling is antiadrenergic in limiting the increase in Ca\(^{2+}\) transient and shortening amplitude and also lessens APD. We believe NOS3 signaling may be acting as an endogenous β-blocker (31) protecting against arrhythmias. β-Blockers have been found to reduce sudden cardiac death in heart failure (33a).

\( l^-\)-NIO is a selective NOS3 inhibitor (50) and did not have any effect in NOS3\(^{-/-}\) myocytes at 10 μM. Therefore, 10 μM \( l^-\)-NIO did not appear to have any nonspecific (e.g., NOS1 inhibition) effects under our experimental conditions. As discussed, acute NOS3 inhibition with \( l^-\)-NIO in WT myocytes further increased EADs, aftercontractions, \( I_{Ca} \), APD\(_{90}\), Ca\(^{2+}\) transient, and shortening amplitude. Because similar results were observed with NOS3 knockout or inhibition, we are confident that NOS3 signaling has antiadrenergic and antiarrhythmic effects.

Although we found significant effects of NOS3 knockout and inhibition on β-AR-stimulated myocyte function, NOS3 signaling may be more important in protecting the heart. A study found that, after chronic pressure overload, NOS3\(^{-/-}\) mice had increased hypertrophy, fibrosis, and contractile dysfunction compared with WT mice (41). In addition, mice with cardiac myocyte-specific NOS3 overexpression had limited hypertrophy and contractile dysfunction after pressure overload and myocardial infarction (10, 23). Furthermore, it is known that \( I_{Ca} \) plays a role in hypertrophy (14). Ca\(^{2+}\) influx via \( I_{Ca} \) activates calcineurin, leading to nuclear factor of activated T cells dephosphorylation and the activation of hypertrophic signaling. Exogenous NO-mediated inhibition of \( I_{Ca} \) can in-
hibit this calcineurin activation (18). Ca\(^{2+}\) influx via \(I_{Ca}\) also leads to apoptosis (12) and arrhythmias (1). Thus increased Ca\(^{2+}\) influx via \(\beta\)-AR-stimulated \(I_{Ca}\) can be detrimental to the myocyte. Interestingly, it has been observed that NOS3 expression is decreased in human heart failure (16). Thus we believe that NOS3 plays an important, protective role against toxic sympathetic activation by reducing the L-type Ca\(^{2+}\) current and APD.

**REFERENCES**


