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Permalink
https://escholarship.org/uc/item/1k3008s1

Journal
Journal of molecular and cellular cardiology, 103

ISSN
0022-2828

Authors
Gray, CBB
Suetomi, T
Xiang, S
et al.

Publication Date
2017-02-01

DOI
10.1016/j.yjmcc.2017.01.002

Peer reviewed
CaMKIIδ subtypes differentially regulate infarct formation following ex vivo myocardial ischemia/reperfusion through NF-κB and TNF-α

Charles B.B. Gray, Takeshi Suetomi, Sunny Xiang, Shikha Mishra, Erik A. Blackwood, Christopher C. Glembotski, Shigeki Miyamoto, B. Daan Westenbrink, Joan Heller Brown

ABSTRACT

Deletion of Ca2+/calmodulin-dependent protein kinase II delta (CaMKIIδ) has been shown to protect against in vivo ischemia/reperfusion (I/R) injury. It remains unclear which CaMKIIδ isoforms and downstream mechanisms are responsible for the salutary effects of CaMKIIδ gene deletion. In this study we sought to compare the roles of the CaMKIIαδ and CaMKIIδδ subtypes and the mechanisms by which they contribute to ex vivo I/R damage. WT, CaMKIIδδKO, and mice expressing only CaMKIIαδ or αδ were subjected to ex vivo global ischemia for 25 min followed by reperfusion. Infarct formation was assessed at 60 min reperfusion by triphenyl tetrazolium chloride (TTC) staining. Deletion of CaMKIIδδ conferred significant protection from ex vivo I/R. Re-expression of CaMKIIδδ in the CaMKIIδδKO background reversed this effect and exacerbated myocardial damage and dysfunction following I/R, while re-expression of CaMKIIαδ was protective. Selective activation of CaMKIIδδ in response to I/R was evident in a subcellular fraction enriched for cytosolic/membrane proteins. Further studies demonstrated differential regulation of nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB) and tumor necrosis factor alpha (TNF-α) expression by CaMKIIδδ and CaMKIIαδ. Selective activation of CaMKIIαδ was also observed and associated with NF-κB activation in neonatal rat ventricular myocytes (NRVMs) subjected to oxidative stress. Pharmacological inhibition of NF-κB or TNF-α significantly ameliorated infarct formation in WT mice and those that re-express CaMKIIαδ, demonstrating distinct roles for CaMKIIδδ subtypes in I/R and implicating acute activation of CaMKIIαδ and NF-κB in the pathogenesis of reperfusion injury.

1. Introduction

The calcium/calmodulin-dependent protein kinase II (CaMKII) is a dodecameric enzyme consisting of subunits encoded by four different genes known as CaMKIα, β, γ, and δ. The predominant cardiac isofrom is CaMKIIδδ and it is alternatively spliced in the heart to generate CaMKIIαδ and CaMKIIγδ as well as other minor subtypes [1–5]. We have generated global and cardiac specific knockouts of CaMKIIδ and demonstrated that deletion of this protein ameliorates heart failure development in response to pressure overload, Gqγ expression, and isoproterenol infusion [6–8]. We further reported that deletion of CaMKIIδδ diminishes infarct development in response to in vivo ischemia/reperfusion [9]. Other studies using CaMKII inhibitory peptides or knock-ins of activation-deficient CaMKII have similarly concluded that CaMKIIδδ activation by a range of cardiac insults, including myocardial infarction, is deleterious [10–13]. In all of the aforementioned studies both the CaMKIIαδ and CaMKIIγδ subtypes of CaMKIIδδ were genetically deleted or inhibited. Accordingly it is not yet known which subtype is responsible for the protective effect of ablating CaMKIIδδ activity in the heart.

The studies reported here use mice in which CaMKIIδδ deletion has been restored by crossing CaMKIIδδKO mice with transgenic lines expressing either the CaMKIIαδ (αδTG/δKO) or CaMKIIγδ (γδTG/δKO) subtype [14]. This approach allowed us to examine the unique roles of...
CaMKIIδα and CaMKIIδc in cardiomyocyte survival and infarct formation in response to I/R. We demonstrate that CaMKIIδc expression reverses and exacerbates the diminished I/R damage observed in CaMKIIδKO mouse hearts whereas CaMKIIδα expression further attenuates I/R damage. The difference in infarct development observed in δαTG/δKO and δcTG/δKO mice is associated with greater I/R-induced inhibitor of kappa B kinase (IKK) and NF-κB activation in δcTG/δKO mice. CaMKIIδα-mediated NF-κB activation is recapitulated in NRVMs exposed to oxidative stress, and selective activation of CaMKIIδc in a cytosol/membrane fraction is observed in NRVMs exposed to oxidative stress and in hearts exposed to I/R. TNF-α expression is also selectively increased in hearts from δcTG/δKO mice following I/R. Blocking either IKK activation or TNF-α signaling diminished infarct development in δcTG/δKO as well as in WT mice. These data suggest that selective activation of the CaMKIIδc subtype in cardiomyocytes regulates cardiac-autonomous pro-inflammatory signaling events that contribute to ischemia/reperfusion injury.

2. Methods

2.1. Transgenic animals

Transgenic Black Swiss mice in which the predominant cardiac subtypes of CaMK, CaMKIIδα and CaMKIIδc, are over expressed were generated in our laboratory and characterized as described [15,16]. Conventional CaMKIIδKO mice were generated and characterized as previously described [6]. CaMKIIδα and CaMKIIδc transgenic mice were crossed with conventional CaMKIIδKO mice to generate mice that express only CaMKIIδα or CaMKIIδc. We refer to these animals as CaMKIIδαTG/δKO and CaMKIIδcTG/δKO. All mice used in the present study were male at 8 weeks of age, unless otherwise noted. Animal studies were performed in accordance with the NIH Guide for the Care and Use of Laboratory Animals and approved by the Institutional Animal Care and Use Committees of University of California at San Diego.

2.2. CaMKII activity assay

CaMKII activity was measured in ventricular homogenate using Syntide-2, a synthetic CaMKII-specific substrate peptide. Hearts were isolated and ventricles homogenized in lysis buffer (50 mmol/L HEPES, 10% ethylene glycol, 2 mg/mL BSA, 5 mmol/L EDTA, pH 7.5), and assayed immediately without freezing. The assay buffer contained 50 mmol/L HEPES, 10 mmol/L magnesium acetate, 1 mg/mL BSA, 20 μmol/L Syntide-2, 1 mmol/L DTT, 400 nM γ-[32P]ATP, pH 7.5 and either 1 mmol/L EGTA (for autonomous activity) or 500 μmol/L CaCl2, plus 1 μmol/L calmodulin (for maximal activity). The reaction was carried out at 30 °C for 10 min and blotted onto Whatman P81 phosphocellulose paper.

2.3. Heart tissue fractionation procedure

Mice were killed by cervical dislocation, and hearts were quickly removed and placed in ice-cold Ca2+-free Krebs-Henseleit buffer. Aortas were cannulated and hearts perfused by gravity flow on a Langendorff perfusion system (Radnoti LLC) at 37 °C and a constant pressure of 80 mm Hg with a modified Krebs-Henseleit buffer solution containing (in mmol/L): 2.0 CaCl2, 130 NaCl, 5.4 KCl, 11 dextrose, 2 pyruvate, 0.5 MgCl2, 0.5 NaH2PO4, and 25 NaHCO3 aerated with 95% oxygen and 5% carbon dioxide, pH 7.4. To measure infarct size, hearts were subjected to 25-minute global ischemia and 1-hour reperfusion; the ventricles were then frozen and cut transversely into 5 slices of equal thickness. The slices were then incubated in 1% TTC/PBS and fixed in 10% formalin-PBS for 24 h. Fixed slices were then scanned, and ImageJ was used to measure and calculate the size of the infarct area and the total area. For experiments utilizing BMS-345541 (Sigma-Aldrich) the drug was dissolved in Krebs-Henseleit buffer solution at a concentration of 5 μmol/L and was present throughout the I/R protocol. For those using etanercept, the drug was present for the entire I/R procedure at a concentration of 5 μg/mL. To assess cardiac function, a water-filled balloon connected to a pressure transducer (Gould Statham P23 ID) was inserted into the left ventricle through the left atrium to monitor left ventricular developed pressure (LVPD); data collected using Powerlab, were processed with AD Instruments Chart 4 software (v4.12). Hearts were submerged in warm KHB (37°C) throughout the perfusion. Functional recovery was expressed as a percentage of pre-ischemic LVPD.

2.4. Neonatal rat ventricular myocyte (NRVM) isolation and adenoviral infection

Neonatal rat ventricular myocytes (NRVMs) were isolated from 1 to 2-day-old Sprague-Dawley rat pups, digested with collagenase, plated at density of 3.5 × 10^4/cm² and maintained overnight in Dulbecco’s modified Eagle’s medium (DMEM) supplemented with 10% fetal calf serum and antibiotics (100 units/mL penicillin and 100 μg/mL streptomycin). Prior to adenoviral infection, isolated NRVMs were transferred to serum-free medium and infected with CaMKIIδα or δc adenovirus at 10, 30, 50, 100, 300 multiplicity of infection (MOI) for 3 h. Cells were washed and maintained in serum-free medium for an additional 21 h prior to treatment with H2O2 or vehicle. To assess changes in nuclear and cytosolic/membrane fractions, NRVMs were fractionated according to a previously reported protocol [17]. Purity was determined using the cytosolic marker Rho GDP dissociation inhibitor (RhoGDI) and the nuclear marker Lamin A/C.

2.5. Transthoracic echocardiography

Echocardiography was performed using the VisualSonics VeVo 770 Imaging System (VisualSonics, Toronto, Canada) equipped with high-frequency 30 MHz probe, as described [18]. Body temperatures were maintained between narrow ranges (37.0 ± 1.0°C) to avoid confounding effects of hypothermia.

2.6. Isolated perfused (ex vivo) I/R

Mice were killed by cervical dislocation, and hearts were quickly removed and placed in ice-cold Ca2+-free Krebs-Henseleit buffer. Aortas were cannulated and hearts perfused by gravity flow on a Langendorff perfusion system (Radnoti LLC) at 37 °C and a constant pressure of 80 mm Hg with a modified Krebs-Henseleit buffer solution containing (in mmol/L): 2.0 CaCl2, 130 NaCl, 5.4 KCl, 11 dextrose, 2 pyruvate, 0.5 MgCl2, 0.5 NaH2PO4, and 25 NaHCO3 and aerated with 95% oxygen and 5% carbon dioxide, pH 7.4. To measure infarct size, hearts were subjected to 25-minute global ischemia and 1-hour reperfusion; the ventricles were then frozen and cut transversely into 5 slices of equal thickness. The slices were then incubated in 1% TTC/PBS and fixed in 10% formalin-PBS for 24 h. Fixed slices were then scanned, and ImageJ was used to measure and calculate the size of the infarct area and the total area. For experiments utilizing BMS-345541 (Sigma-Aldrich) the drug was dissolved in Krebs-Henseleit buffer solution at a concentration of 5 μmol/L and was present throughout the I/R protocol. For those using etanercept, the drug was present for the entire I/R procedure at a concentration of 5 μg/mL. To assess cardiac function, a water-filled balloon connected to a pressure transducer (Gould Statham P23 ID) was inserted into the left ventricle through the left atrium to monitor left ventricular developed pressure (LVPD); data collected using Powerlab, were processed with AD Instruments Chart 4 software (v4.12). Hearts were submerged in warm KHB (37°C) throughout the perfusion. Functional recovery was expressed as a percentage of pre-ischemic LVPD.
2.8. RT-PCR

RNA extraction for real time analysis was performed using the solid-phase RNeasy purification kit from Qagen (Venlo, Netherlands). First strand cDNA synthesis for Real time PCR was performed using the High Capacity cDNA Reverse Transcription Kit (Applied Biosystems, Grand Island, NY). Gene expression was determined using Taqman® Universal PCR master mix, Cy5-labeled Taqman® probe for TNF-α and IL-6 and FAM-labeled Taqman® probe for GAPDH (Applied Biosystems).

3. Statistical analysis

Data are presented as mean ± SEM as indicated and were analyzed by 2-tailed Student t-test between 2 groups or by ANOVA when 3 or more groups were compared. P values <0.05 were considered statistically significant.

4. Results

To examine the independent roles of the CaMKIIδB and δC subtypes in the heart we restored either δB or δC expression in a CaMKIIδ-null (KO) background. The resulting animals express only δB (δB TG/δKO) or only δC (δC TG/δKO). Survival of WT, KO, δB TG/δKO, and δC TG/δKO mice was assessed. Deletion of CaMKIIδ produced no overt phenotypic changes and did not affect survival relative to WT mice as shown previously [6]. δB TG/δKO animals also survived normally for at least 6 months. In contrast, the δC TG/δKO animals, like the previously studied δC KO [16], exhibited premature death with ~20% survival by 21 weeks (Fig. 1A). Expression of the CaMKIIδB and δC subtypes also had markedly different effects on in vivo cardiac function. Echocardiography on 6–8 week old mice revealed that fractional shortening (FS) was decreased by 63% in δC TG/δKO mice compared to WT mice (Fig. 1B) while δB TG/δKO animals did not display cardiac dysfunction.

We previously demonstrated that CaMKIIδ deletion attenuates I/R injury in response to in vivo left anterior descending coronary artery occlusion and subsequent reperfusion [9]. To examine the cardiac-intrinsic role of CaMKIIδ in I/R we performed ex vivo I/R experiments on isolated perfused hearts from 8–week-old mice. Infarct formation following 25 min ischemia and 1 h reperfusion was determined by TTC staining of heart sections. In WT animals, ex vivo I/R induced infarcts comprising 36.2 ± 2.5% of the cross-sectional area. Infarcts were significantly smaller, only 24.1 ± 1.4%, in CaMKIIδ KO mice (Fig. 2A, B). Thus regulation of infarct development by CaMKIIδ is evident not only in vivo but also in an ex vivo I/R model.

Hearts from δB TG/δKO mice were then examined and found to be protected against ex vivo I/R damage, with infarcts measuring 12.2 ± 1.9% of cross-sectional area. Conversely, in δC TG/δKO mice, the protective effect of CaMKIIδ gene deletion was lost with infarcts measuring 45.2 ± 1.8% of the cross-sectional area, significantly larger than those of WT, KO, and δB TG/δKO (Fig. 2A, B). Assessment of left ventricular developed pressure (LVDP) recovery during reperfusion confirmed that expression of CaMKIIδB in CaMKIIδKO mice exacerbates I/R damage while expression of CaMKIIδC does not (Supplemental Fig. 1).

CaMKIIδ is known to be activated during ex vivo I/R [19,20], but previous experiments have not assessed subtype-specific CaMKIIδ activation. Although we previously demonstrated that δB and δC can be equivalently activated by several pharmacological interventions [14], we wondered if I/R might lead to differential activation of the two subtypes. To assess I/R-induced activation of CaMKIIδ we analyzed phosphorylation of CaMKIIδ at its autophosphorylation site threonine-286. The increases in CaMKIIδ autophosphorylation observed in whole cell lysates from hearts of δB TG/δKO and δC TG/δKO mice subjected to I/R were equivalent (Fig. 3A).

Many substrates of CaMKIIδB (e.g. phospholamban, RyR2, and histone deacetylase 4) localize to the cytosol or the cytosolic face of the cardiac sarcoplasmic reticular (SR) membrane. Thus we carried out further studies using a subcellular fraction enriched for cytosolic and membrane proteins. Strikingly in this fraction we observed differential activation of the δB and δC subtypes in response to I/R. Indeed whereas no increases in CaMKIIδB autophosphorylation were observed in cytosolic/membrane fractions from δB TG/δKO mouse hearts, there was a >3-fold increase in autophosphorylated CaMKIIδ in cytosolic/membrane-enriched fractions from δC TG/δKO hearts (Fig. 3B).

Our earlier studies examining in vivo I/R damage linked the deleterious effects of CaMKIIδ to activation of IKK and subsequent NF-κB nuclear accumulation [9]. To determine which CaMKIIδ subtype was responsible, and also to determine if CaMKIIδB-mediated NF-κB activation can occur in the absence of systemic factors (e.g. leukocyte infiltration), we examined regulation of IKK and NF-κB by I/R in the ex vivo heart. The phosphorylation of IKK was found to be elevated during ex vivo reperfusion in δB TG/δKO mice but not in δB TG/δKO mice (Fig. 4A). Furthermore I/R-mediated activation of IKK in δC TG/δKO mice was associated with an increased nuclear localization of the p65 subunit of NF-κB, which was not observed in δB TG/δKO animals (Fig. 4B).

Nuclear p65 translocation would be expected to result in transcriptional activation of NF-κB target genes. Thus further evidence that differences in NF-κB activation in δB TG/δKO and δC TG/δKO are functionally significant, we measured mRNA levels of genes regulated by NF-κB. Ischemia/reperfusion increased interleukin 6 (IL-6) mRNA in hearts from δC TG/δKO mice to a greater extent than in those from δB TG/δKO mice (Fig. 5A). Even more striking was the robust increase in TNF-α expression in δC TG/δKO mice and the absence of upregulation of this gene in δB TG/δKO animals (Fig. 5B).
To confirm that oxidative stress can lead to selective activation of CaMKIIδ and of NF-κB in a cardiomyocyte-autonomous fashion, we infected NRVMs with adenovirus expressing CaMKIIδ or CaMKIIδC. Cells were infected with a range of MOIs of CaMKIIδ or δC virus and subsequently treated with 50 μM H₂O₂ for 30 min to elicit CaMKII and NF-κB activation. In NRVM whole cell lysates we observed equivalent activation of CaMKIIδ and CaMKIIδC in response to H₂O₂ at all MOIs (Fig. 6A, top panel), as quantitated using an MOI of 50 (Fig. 6A lower panel). In NRVM lysates that were fractionated to enrich for cytosolic and membrane proteins, however, there was significantly greater activation of CaMKIIδC following H₂O₂ treatment (Fig. 6B). We further determined that expression of CaMKIIδC, but not CaMKIIδB, enhanced H₂O₂-mediated I κB alpha (IκBα) degradation (Fig. 6C) and nuclear p65 accumulation (Fig. 6D). These data, like those obtained in the isolated perfused heart (Figs. 3 and 4) suggest that oxidative stress-induced CaMKIIδC activation in the cytosolic/membrane compartment is associated with activation of NF-κB.

To demonstrate that the deleterious effects of CaMKIIδC activation seen in the isolated perfused heart were mediated by IKK/NF-κB signaling we blocked IKK with the pharmacological inhibitor BMS-345541 (BMS) [21]. Since this drug had not, to our knowledge, been used in the ex vivo perfused heart we evaluated its efficacy and determined a dose (5 μmol/L) that sequestered p65 in the cytosol/membrane fraction (Supplemental Fig. 2). Hearts from δC/δKO mice exposed to 5 μmol/L BMS or vehicle prior to and throughout the I/R protocol. The results were similar to those obtained with IKK/NF-κB inhibition i.e. infarct size was significantly reduced in WT and δC/δKO mice and was not further reduced in WT or δC/δKO mice exposed to 5 μmol/L BMS or vehicle prior to and throughout the I/R protocol. Infarct size was significantly reduced by BMS administration in WT and δC/δKO mice, while the already diminished infarct formation that was observed in δC/δKO animals was not affected (Fig. 7). CaMKIIδKO animals showed a modest but significant further reduction in infarct size.

In light of the selective increase in TNF-α mRNA in δC/δKO mice, and evidence that active TNF-α can be produced in and secreted from the isolated perfused heart [22], we asked whether TNF-α mediated the deleterious effects of CaMKIIδC. For these studies we used etanercept, which blocks the effects of TNF-α by preventing its interaction with TNF-α receptors [23,24]. Etanercept was perfused at 5 μg/mL prior to and throughout the I/R protocol. The results were similar to those obtained with IKK/NF-κB inhibition i.e. infarct size was significantly reduced in WT and δC/δKO mice and was not further reduced in δC/δKO animals. CaMKIIδKO animals showed modest but significant further reductions in infarct size in the presence of etanercept (Fig. 8). These findings reveal a surprisingly important role for autocrine and/or paracrine TNF-α signaling in the ex vivo isolated perfused heart during I/R, demonstrate that this process is regulated by CaMKIIδC, and establish an essential cardiac-intrinsic role for NF-κB in I/R injury (Fig. 9).
5. Discussion

Our laboratory previously demonstrated that mice in which CaMKIIδ was selectively deleted from cardiomyocytes exhibited diminished infarct formation in response to in vivo I/R [9]. These experiments provided evidence that CaMKIIδ activation in cardiomyocytes mediates the deleterious effects of I/R injury but did not address the question of which subtype(s) of CaMKIIδ were responsible for cardiomyocyte death in response to I/R. Here we characterize and utilize mice in which the CaMKIIδB or CaMKIIδC isoforms are expressed in the CaMKIIδKO animals to independently determine the role of each of these isoforms in cardiomyocyte CaMKII signaling. In addition we analyzed I/R damage in the ex vivo isolated perfused heart where the role of systemic inflammatory factors is eliminated. Our studies demonstrate that signals that are rapidly and locally generated regulate infarct development in the ex vivo heart and are significantly attenuated in the absence of CaMKIIδ. We further show that CaMKIIδ re-expression in cardiomyocytes reverses the attenuation of infarct formation seen in CaMKIIδKO mice. In contrast CaMKIIδB re-expression further limits infarct development compared to that observed in KO mice.

While total CaMKIIδ expression and maximal activity are somewhat higher in δCTG/δKO mice (Supplemental Fig. 3 B) the amount of activated (Ca2+-autonomous) CaMKII is similar in δCTG/δKO and δBTG/δKO animals (Supplemental Fig. 3 A). Thus it is unlikely that differential baseline levels of active CaMKIIδ explain the response of δCTG/δKO versus δBTG/δKO animals to I/R. There may, however, be a greater propensity for activation of inflammatory responses when CaMKIIδC is activated thus we determined whether I/R could lead to selective increases in NF-κB activation in δCTG/δKO mice. NF-κB activation was assessed by measuring mRNA transcripts of genes regulated by NF-κB, A, IL-6 B, TNF-α. Data are mean ± SEM values from 4 mice. *P < 0.05 vs sham #P < 0.05 vs δCTG/δKO.

![Fig. 4. The NF-κB pathway is activated in CaMKIIδCTG/δKO mice following reperfusion. A. Activation of IKK was assessed in δTG/δKO and δCTG/δKO mice using an antibody specific for auto-phosphorylated IKKα/β. B. NF-κB p65 accumulation was assessed in nuclear extracts made from hearts of δTG/δKO and δCTG/δKO mice subjected to ex vivo I/R. Data are mean ± SEM values from 6 mice. P < 0.05 vs sham.](image)

![Fig. 5. Genes downstream of NF-κB are upregulated in CaMKIIδCTG/δKO mice after ex vivo I/R. NF-κB activation was measured by assessing mRNA transcripts of genes regulated by NF-κB, A, IL-6 B, TNF-α. Data are mean ± SEM values from 4 mice. *P < 0.05 vs sham #P < 0.05 vs δCTG/δKO.](image)
was independent of necrosis [9] and we confirmed this in the current ex vivo study (Supplemental Fig. 4). Accordingly we suggest that there is a direct effect of CaMKII on NF-κB activation. This conclusion is further supported by our current data showing that acute activation of CaMKIIδC with H2O2 elicits NF-κB activation in NRVMs and by our previous demonstration that adenoviral expression of activated CaMKIIδC in NRVMs induces IKK activation [9].

Strikingly, we show here that NF-κB activation in response to I/R is enhanced by cardiac expression of CaMKIIδC but not CaMKIIδB. This is consistent with the finding that phosphorylation of the upstream kinase IKK is increased by I/R in ακ/κδKO but not in δκ/αδKO animals. Furthermore, we demonstrate that I/R increases activation of CaMKIIδC but not of CaMKIIδB in the cytosol/membrane, where IKK is localized. We previously reported that despite its nuclear localization in cardiomyocytes [29] CaMKIIδN is not strictly confined to the nucleus [14] but is in fact present in the cytosol/membrane compartment (Fig. 3B). It remains unclear why there is selective activation of CaMKIIδC and not CaMKIIδN in this location. Nevertheless our observations in NRVMs confirm that there is differential activation of equivalently expressed levels of CaMKIIδB and δκ by oxidative stress and further indicate an association between cytosolic CaMKIIδC autophosphorylation and subsequent IκBα degradation and nuclear accumulation of p65. Notably another recent report confirmed the ability of CaMKIIδ-C subtypes to undergo differential posttranslational modification during reperfusion [30].

Previous studies using pharmacological inhibitors to demonstrate involvement of CaMKIIδC in ex vivo I/R damage linked the effects of CaMKII to phosphorylation of PLN and RyR2 and subsequent Ca2+ dysregulation [31], supporting the hypothesis that rapid phosphorylation of CaMKII targets was a driver of myocardial injury. Indeed, we originally considered it unlikely that transcriptional regulation by CaMKIIδC-mediated activation of NF-κB could play a significant role in determining cell viability over the course of only one hour of reperfusion. Surprisingly, however, we found that inhibition of either IKK or TNF-α had a profound effect on infarct formation not only in δκ/αδKO but also in WT mouse hearts subjected to 25 min ex vivo ischemia and 60 min reperfusion.

Recent studies have shown that receptor-interacting protein kinase 3 (RIP3) plays a role in TNF-α-mediated cell death through formation of the necrosome [32]. RIP3 phosphorylates and activates CaMKII during I/R [33] accordingly TNF-α could participate in a deleterious positive feedback loop leading to sustained CaMKIIδC and NF-κB activation. The experiments presented in this study clearly indicate that TNF-α signaling and myocardial NF-κB activation are mechanisms by which CaMKIIδC elicits infarct formation in the isolated perfused heart. This signaling would likely be further enhanced and sustained by Ca2+ dysregulation resulting from CaMKII-mediated phosphorylation of SR substrates and increases in reactive oxygen species (ROS) during I/R [19,34,35].

Paradoxically, some reports indicate that NF-κB may be protective in I/R injury [36,37] while others demonstrate a deleterious role for NF-κB activation [25,38]. Importantly, these studies differ in how I/R is elicited and how NF-κB is inhibited, thus resolution of these conflicting conclusions remains elusive. In the current study we have demonstrated that CaMKIIδC expressed in cardiomyocytes mediates NF-κB activation, TNF-α induction and infarct development during I/R and that these events occur rapidly and in the absence of systemic inflammatory factors. Our data contribute to the understanding of the dichotomous effects of NF-κB by clearly demonstrating an adverse cardiomyocyte-autonomous role of NF-κB activation in I/R injury.

While we demonstrate that cardiac TNF-α expression during I/R is mediated by CaMKIIδC activation in cardiomyocytes, we do not know...
the extent to which TNF-α is formed in and secreted from these cells. Cardiac-resident macrophages and other non-myocytes are potential sources of TNF-α and could thus act in an autocrine or paracrine fashion to affect cardiomyocyte survival. The extent to which CaMKIIδ activation in myocytes sends signals to other cells is not clear, but our studies demonstrate that the cardiomyocyte initiates signals though CaMKIIδ that lead to upregulation of TNF-α. TNF-α inhibitors such as etanercept have been used to inhibit TNF-α signaling in patients with various autoimmune disorders [39]. Effects of TNF-α inhibitors on cardiovascular disease outcomes have also been evaluated with uncertain results that could in part be due to systemic responses to sustained antibody administration [28]. Such detrimental effects would not be expected to occur during short-term treatment thus use of TNF-α inhibitors could be of value if employed at the onset of reperfusion following primary percutaneous intervention for myocardial infarction.

In summary, we demonstrate that the δC isoform of CaMKII contributes significantly to myocardial damage following ex vivo I/R. Signaling occurs through NF-κB and TNF-α and acute inhibition of the generation or function of these molecules has a very robust protective effect in WT animals and in those expressing CaMKIIδC. Importantly, we show that these events occur during a much shorter timeframe than would have been predicted by previous studies of CaMKIIδ and NF-κB signaling in in vivo I/R, and that these events occur in the absence of systemic factors such as infiltration of cells originating outside of the heart. CaMKII inhibition is predicted to be of therapeutic benefit in a number of contexts. Our results suggest that selective CaMKIIδC inhibition would confer the most benefit over blockade of all cardiac CaMKII isoforms although specific means of locally inhibiting the δC isoform do not yet exist. An alternative approach would be to acutely block events that occur downstream of CaMKIIδC activation during I/R such as IKK/NF-κB activation or TNF-α signaling.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.yjmcc.2017.01.002.

**Sources of funding**

This work was supported by the National Institutes of Health (NIH) grants R01-HL085577, and R01 HL105242 to J.H. Brown. S. Miyamoto is supported by the American Heart Association 15GRNT 2297009 and NIH R56 HL097037. B.D. Westenbrink is supported by the Netherlands Heart Institute, the Dutch Heart Foundation (grant 2012T066) and the Netherlands Organisation for Scientific Research.

Fig. 7. Inhibition of IKK ameliorates I/R damage. Vehicle and BMS-345541 (5 μmol/L) were perfused into hearts from WT, KO, δCTG/δKO, and δBTG/δKO animals. Infarct size was measured via TTC staining following 1hr of reperfusion. Data are mean ± SEM values from 4 to 8 mice. *P < 0.05 vs veh.

Fig. 8. Inhibition of TNF-α ameliorates I/R damage. Vehicle or etanercept (5 μg/mL) were perfused into hearts from WT, KO, δCTG/δKO, and δBTG/δKO animals. Infarct size was measured via TTC staining following 1hr of reperfusion. Data are mean ± SEM values from 4 to 8 mice. *P < 0.05 vs veh.

Fig. 9. Summary of findings. NF-κB nuclear translocation and subsequent TNF-α upregulation during I/R is mediated by cytosolic CaMKIIδC activation.
Research (grant 016.176.147). C.B.B. Gray was supported by the NIGMS Graduate Training Program in Cellular and Molecular Pharmacology (T32 GM007752). S. Xiang was supported by the Cardiovascular Physiology and Pharmacology Training grant 5T32HL007444. C.C. Gembotski was supported by the NIH grants R01 HL75573, R01 HL104535, and P01 HL085577. T. Sueto is supported by the Uehara Memorial Foundation (Japan).

Disclosures

None.

Acknowledgements

We thank Sarah Shires and Asa Gustafsson for their assistance with echocardiography, Melissa Barlow for animal husbandry and echocardiography, and Jeff Smith for his assistance in adenosivual synthesis and amplification.

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