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ARTICLE ADDENDUM

Predominant contribution of L-type Cav1.2 channel stimulation to impaired intracellular calcium and cerebral artery vasoconstriction in diabetic hyperglycemia

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ABSTRACT

Enhanced L-type Ca\(^{2+}\) channel (LTCC) activity in arterial myocytes contributes to vascular dysfunction during diabetes. Modulation of LTCC activity under hyperglycemic conditions could result from membrane potential-dependent and independent mechanisms. We have demonstrated that elevations in extracellular glucose (HG), similar to hyperglycemic conditions during diabetes, stimulate LTCC activity through phosphorylation of CaV1.2 at serine 1928. Prior studies have also shown that HG can suppress the activity of K\(^{+}\) channels in arterial myocytes, which may contribute to vasoconstriction via membrane depolarization. Here, we used a mathematical model of membrane and Ca\(^{2+}\) dynamics in arterial myocytes to predict the relative roles of LTCC and K\(^{+}\) channel activity in modulating global Ca\(^{2+}\) in response to HG. Our data revealed that abolishing LTCC potentiation normalizes [Ca\(^{2+}\)]\(_i\), despite the concomitant reduction in K\(^{+}\) currents in response to HG. These results suggest that LTCC stimulation may be the primary mechanism underlying vasoconstriction during hyperglycemia.

KEYWORDS
arterial myocytes; diabetes; ion channels; mathematical modeling; sensitivity analysis

Introduction

Diabetes is a devastating disease that affects millions worldwide, and is a major risk factor for stroke, hypertension, heart disease, and other pathological conditions. Hyperactivity of L-type Ca\(^{2+}\) channels (LTCCs) in arterial myocytes of small resistance vessels contributes to vascular complications during diabetes. This is in part attributed to the effects of hyperglycemia (elevated blood glucose). We recently gained novel mechanistic insights into this phenomenon and demonstrated that stimulation of vascular LTCCs in response to elevated glucose (HG) is dependent upon phosphorylation of the LTCC pore forming subunit CaV1.2 at serine 1928 (S1928) via anchoring of the cAMP-dependent protein kinase (PKA) by the scaffolding protein AKAP150. Glucose-mediated potentiation of LTCCs led to a significant increase in intracellular Ca\(^{2+}\) concentration ([Ca\(^{2+}\)]\(_i\)) and constriction in cells and arteries from wild-type (WT) mice. Conversely, in arterial myocytes and arteries from knock-in mice expressing a CaV1.2 with S1928 mutated to alanine (S1928A) to prevent phosphorylation at this site, glucose-mediated changes in LTCC activity, [Ca\(^{2+}\)]\(_i\), and excessive vasoconstriction were prevented.

An increase in extracellular glucose also impacts the function of other ion channels in arterial myocytes. Indeed, acute and chronic exposure to HG has been shown to suppress the expression and/or activity of K\(^{+}\) channels in coronary, mesenteric, and cerebral arterial myocytes. K\(^{+}\) channels are key regulators of arterial myocyte excitability and vascular reactivity due to their influence on the membrane potential (E\(_m\)). Inhibition of K\(^{+}\) channel function depolarizes arterial myocyte E\(_m\), which in turn increases LTCC activity and Ca\(^{2+}\) influx, leading to global raises in [Ca\(^{2+}\)]\(_i\), that induces arterial myocyte contraction and vasoconstriction. Thus, it is conceivable that reduced
K⁺ channel activity contributes to enhanced myogenic tone in the presence of HG. However, observations of HG-induced K⁺ channel suppression contrast with our finding that HG failed to evoke changes in [Ca²⁺]ᵢ in arterial myocytes or vasoconstriction in arteries from S1928A mice. The lack of a glucose effect in myocytes and arteries from S1928A mice is unlikely due to differences in basal K⁺ channel density, as protein abundance for voltage-gated K⁺ (KV) KV2.1 subunit, and large-conductance Ca²⁺-activated BKCa α and β1 subunits, which regulate arterial myocyte excitability and are glucose-sensitive, was similar between WT and S1928A arteries. Changes in CaV1.2 expression are also unlikely, as the S1928A point mutation itself did not alter the abundance of CaV1.2. Consistent with this, pressure-induced constriction, which is highly dependent on LTCC and K⁺ channel function, resulted in a vascular tone of equal magnitude in WT and S1928A arteries under normal extracellular glucose concentrations (i.e. 10 mM D-glucose). Overall, our previous data suggest a relatively small influence of glucose-induced K⁺ channel inhibition and consequent Eₑ depolarization to arterial myocyte hypercontractility in response to HG. These findings point toward a key role for CaV1.2 phosphorylation at S1928 in global Ca²⁺ increases and vasoconstriction in response to HG that is, at least partly, independent of changes in Eₑ. Here, we used an established mathematical model of arterial myocyte electrophysiology and Ca²⁺ dynamics to quantitatively compare the relative contribution of K⁺ channels and LTCCs in modulating Eₑ and [Ca²⁺]ᵢ changes in response to HG. Our analysis supports a predominant role of LTCC potentiation (vs. K⁺ channel inhibition) in HG-mediated increase in [Ca²⁺]ᵢ, leading to vasoconstriction of cerebral arteries.

**Results and discussion**

We used the Kapela et al. model of an arterial myocyte to assess changes in [Ca²⁺]ᵢ, when simulating an acute elevation in glucose. Based on previous experimental

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**Figure 1.** LTCCs play a key role in [Ca²⁺]ᵢ regulation during acute hyperglycemic conditions. Simulated (A, B) and experimental (C, D) HG-mediated effects on [Ca²⁺]ᵢ in WT and S1928A cells. To simulate gradual increase of glucose concentration over time, full modification of HG-dependent model parameters is reached after 180 s from the initial administration (indicated by the arrow). Fig. 1C and D are from our previously published study. © AAAS. Reproduced by permission of AAAS. Permission to reuse must be obtained from the rightsholder.
HG targets both Ca\(^{2+}\) and K\(^{+}\) channels to enhance LTCC currents and suppress K\(^{+}\) currents. Under these conditions, our model predicted that HG would lead to a \(\sim\)2-fold increase in [Ca\(^{2+}\)]\(_i\) at steady-state in WT arterial myocytes (Fig. 1A and B). Indeed, this result is similar to our experimental data in isolated arterial myocytes from WT mice (Fig. 1C and D). When potentiation of LTCC activity in response to HG is ablated to simulate lack of S1928 phosphorylation, as in S1928A cells, the predicted increase in [Ca\(^{2+}\)]\(_i\) is limited to \(\sim\)20% (Fig. 1A and B), which again is in agreement with our experimental observations (Fig. 1C and D). These results suggest that changes in [Ca\(^{2+}\)]\(_i\) in arterial myocytes in response to HG are minimal in the absence of S1928 phosphorylation and LTCC potentiation, despite a reduction in K\(^{+}\) channel activity and subsequent E\(_m\) depolarization, which is expected to enhance Ca\(^{2+}\) influx.

To dissect the relative contribution of HG-induced modifications of LTCCs and K\(^{+}\) channels to [Ca\(^{2+}\)]\(_i\), and E\(_m\), we compared the effects of HG on each target in isolation (Fig. 2). Under normal conditions (i.e., in the baseline model assuming 10 mM D-glucose), predicted [Ca\(^{2+}\)]\(_i\) and E\(_m\) are 68 nM and \(-59.4\) mV, respectively. When specific glucose-mediated alterations in K\(^{+}\) channels are simulated E\(_m\) underwent a \(\sim\)5 mV depolarization (Fig. 2B), due to the reduction in outward currents, whereas the increase in [Ca\(^{2+}\)]\(_i\) was limited (\(\sim\)10 nM, Fig. 2A). This limited change in E\(_m\) is similar to that observed by Rainbow et al. in

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**Figure 2.** Effects of glucose-induced modifications on [Ca\(^{2+}\)]\(_i\) and E\(_m\). Predicted variations of [Ca\(^{2+}\)]\(_i\) (A) and E\(_m\) (B) (compared with control) obtained at rest (i.e., absence of external stimuli) when glucose-mediated modifications are included for K\(^{+}\) channels (BKCa and Kv2.1) only (red), for LTCC only, or for both. When glucose concentration is normal resting [Ca\(^{2+}\)]\(_i\) and E\(_m\) are 68 nM and \(-59.4\) mV, respectively. (C, D) Steady-state [Ca\(^{2+}\)]\(_i\) values obtained by clamping the virtual cell at the indicated E\(_m\) with normal glucose or when HG-dependent modifications are included as described in the text.
response to elevations in extracellular glucose. When only glucose-induced LTCC potentiation was simulated $E_m$ was unchanged (Fig. 2B), as expected. However, LTCC potentiation caused a pronounced increase in $[\text{Ca}^{2+}]_i$ ($\sim 30$ nM, Fig. 2A). When both effects were included (Figs 1 and 2B), HG-induced elevations in $[\text{Ca}^{2+}]_i$ and $E_m$ were further enhanced ($\sim 75$ nM and $\sim 6$ mV, Fig. 2A-B). Notably, the effect of HG on $[\text{Ca}^{2+}]_i$ when alterations of all targets were simulated was larger than the sum of the effect at each individual target (Fig. 2B), suggesting potential synergy between LTCC activation and $K^+$ channel inhibition. When simulations were repeated in voltage-clamped cells at different $E_m$ (e.g. $-60$ mV or $-40$ mV) to identify the effect of HG on $[\text{Ca}^{2+}]_i$ independently of $E_m$ variations (Fig. 2C-D), $K^+$ channel inhibition did not affect global $\text{Ca}^{2+}$. However, holding $E_m$ at a more depolarized voltage augmented the HG- (and LTCC-) mediated increase in $[\text{Ca}^{2+}]_i$.

We also analyzed how modulating the activity of all ion currents and transport mechanisms affect $[\text{Ca}^{2+}]_i$ and $E_m$ in response to HG, following the methodology described by Sobie. The results of this statistical process are summarized in the regression coefficients reported in Table 1, which can be used to estimate changes in $[\text{Ca}^{2+}]_i$ and $E_m$ due to given variations in each model parameter. Importantly, our analysis on the HG targets (Fig. 3) showed that variations in $[\text{Ca}^{2+}]_i$ are positively correlated with LTCC activity, while $E_m$ is insensitive to this model parameter. Inhibition of $K^+$ channels, which is weakly correlated with an increase in $[\text{Ca}^{2+}]_i$, has a strong depolarizing effect. Interestingly, modulation of $K_V$ channel activity has a more prominent effect on $[\text{Ca}^{2+}]_i$ and $E_m$ regulation compared with $BK_{Ca}$ channels. We also found that $[\text{Ca}^{2+}]_i$ is strongly affected by the activity of non-selective cation channels (NSCs), which also strongly regulate $E_m$, causing depolarization, and plasma membrane $\text{Ca}^{2+}$-ATPase (PMCA). Thus, this analysis revealed new mechanistic information that warrants further experimental studies to investigate the role of these fluxes in response to HG and their impact on arterial myocyte excitability and vascular reactivity. Overall, the sensitivity analysis confirmed our mechanistic interpretation of the predominant role of LTCC potentiation in HG-mediated increase in $[\text{Ca}^{2+}]_i$, and the secondary role of $K^+$ channels in this outcome.

Our recent study demonstrated that acute elevations in extracellular glucose causes a significant increase in $[\text{Ca}^{2+}]_i$ and constriction in cerebral arterial myocytes and arteries from WT mice. These changes were dependent on increased LTCC activity mediated by phosphorylation of Cav1.2 at S1928. The computational analysis performed here indicates that glucose-induced inhibition of $K^+$ channels in the absence of LTCC hyperactivation (i.e., as it may occur in S1928A myocytes) does not cause appreciable changes in $[\text{Ca}^{2+}]_i$. Yet, LTCC potentiation in response to HG drives significant $[\text{Ca}^{2+}]_i$ enhancement, as it seems to occur in WT myocytes. Note that during chronic elevations in extracellular glucose, as in diabetes, both $E_m$-independent (e.g., PKA-mediated upregulation of LTCC activity) as well as $E_m$-dependent (e.g., downregulation of $K^+$ channel activity leading to depolarization and further LTCC activation) mechanisms synergize to contribute to modulate $[\text{Ca}^{2+}]_i$ in arterial myocytes. Indeed, our simulation studies showed that the increase in $[\text{Ca}^{2+}]_i$ seen with concomitant inhibition of $K^+$ currents and LTCC potentiation is

### Table 1. Regression coefficients. Sensitivity analysis was performed to assess the consequences of changes in all ion channels and transport mechanisms in the model: L-type $\text{Ca}^{2+}$ channels (LTCC), large-conductance $\text{Ca}^{2+}$-activated $K^+$ channels ($BK_{Ca}$), voltage-gated $K^+$ channels ($K_{V2.1}$), unspecified $K^+$ leak channels ($K_{leak}$), $\text{Ca}^{2+}$-activated Cl$^-$ channels ($Cl_{Ca}$), Na$^+$-$K^+$-$Cl^-$ cotransporter (NaKCl), Na$^+$-$K^+$-$\text{ATP}$ase (NaK), Na$^+$-$\text{Ca}^{2+}$ exchanger (NCX), plasma membrane $\text{Ca}^{2+}$-ATPase (PMCA), store-operated $\text{Ca}^{2+}$-permeable non-selective cation channels (SOC), non-selective cation channels (NSC), IP$_3$ receptor (IP$_3$R), SR passive $\text{Ca}^{2+}$ leak (SRleak), ryanodine receptor (RyR), SR $\text{Ca}^{2+}$-$\text{ATP}$ase pump (SERCA). A positive coefficient indicates positive correlation between changes in the observed outcome ($[\text{Ca}^{2+}]_i$ or $E_m$) and a given parameter, and vice versa. Given these coefficients, one can quantify how a change in a certain parameter affects a certain output as explained in the caption of Fig. 3.

| Ion current or transport mechanism | $[\text{Ca}^{2+}]_i$ | $E_m$ |
|-----------------------------------|----------------------|-------|
| LTCC                             | 0.220                | −0.021|
| $BK_{Ca}$                        | −0.025               | 0.135 |
| $K_{V2.1}$                       | −0.054               | 0.298 |
| $K_{leak}$                       | −0.087               | 0.481 |
| $Cl_{Ca}$                        | 9.00e−3              | −0.038|
| NaKCl                            | 1.44e−3              | 0.012 |
| NaK                              | −0.190               | −0.097|
| NCX                              | −0.048               | −0.044|
| PMCA                             | −0.566               | 0.060 |
| SOC                              | 0.100e−3             | 0.51e−3|
| NSC                              | 0.753                | −0.795|
| IP$_3$R                          | 2.00e−3              | 0.35e−3|
| SRleak                           | 1.45e−3              | 2.96e−3|
| RyR                              | −0.76e−3             | 1.65e−3|
| SERCA                            | 1.31e−3              | 1.52e−3|
attenuated when \( E_m \) depolarization is prevented. Our results also suggested a predominant role of \( K_{V2.1} \) (vs. \( BK_Ca \)) in the HG-induced \( E_m \) depolarization. To summarize, our findings confirmed an essential role for CaV1.2 phosphorylation at S1928 in stimulating LTCC activity and vasoconstriction in response to HG. We also demonstrated the power of computational models and population-based statistical approaches in quantifying the relative roles of many elements that interact non-linearly to regulate such complex processes in arterial myocytes.

**Methods**

The Kapela et al. mathematical model of electrophysiology and Ca\(^{2+}\) dynamics in arterial myocytes\(^{17}\) served as the basis for our simulations. This model is a system of non-linear ordinary differential equations describing the main transmembrane fluxes of Ca\(^{2+}\), K\(^{+}\), Na\(^{+}\) and Cl\(^{-}\) involved in \( E_m \) regulation and the mechanisms controlling intracellular (cytosol and sarcoplasmic reticulum, SR) Ca\(^{2+}\) homeostasis. We modified the baseline model to include glucose-dependent effects on LTCCs, \( BK_{Ca} \) and \( K_{V2.1} \) conductances that recapitulate previous experimental observations\(^{3,12,13}\). Specifically, elevated glucose caused a 2-fold increase in LTCC conductance, whereas \( BK_{Ca} \) and \( K_{V2.1} \) currents were reduced by 58 and 63%, respectively.

We performed sensitivity analysis to investigate the influence of the various currents and transporters in the regulation of global Ca\(^{2+}\) and \( E_m \) using an established population-based approach\(^{18}\). The baseline model (i.e., with normal glucose at 10 mM) was used
to simulate a family of 1000 model variants, generated by randomly varying conductances or maximal transport rates of all ion currents and transport mechanisms (Table 1). Specifically, the baseline value of each parameter was independently varied with a log-normal distribution (standard deviation of 0.1), that approximately allows changes within the range −30% to +50%. We assessed the resulting values of $E_m$ and $[\text{Ca}^{2+}]$, for each model variant, and performed multi-variable regression (non-linear iterative partial least squares method) on log-transformed values to correlate the variation in each parameter to the consequent effect on these 2 outputs.\(^{18}\)

All simulations were performed in MATLAB (The MathWorks, Natick, MA, USA) using the stiff ordinary differential equation solver ode15s. Our codes are freely available for download at:

somapp.ucdmc.ucdavis.edu/Pharmacology/bers
or
elegrandi.wixsite.com/grandilab/downloads.

Disclosure of potential conflicts of interest

No potential conflicts of interest were disclosed.

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