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Cardiovascular consequences of $K_{\text{ATP}}$ overactivity in Cantu syndrome

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Cantu syndrome (CS) is characterized by multiple vascular and cardiac abnormalities including vascular dilation and tortuosity, systemic hypotension, and cardiomegaly. The disorder is caused by gain-of-function (GOF) mutations in genes encoding pore-forming (Kir6.1, KCNJ8) and accessory (SUR2, ABCC9) ATP-sensitive potassium (K$_{\text{ATP}}$) channel subunits. However, there is little understanding of the link between molecular dysfunction and the complex pathophysiology observed, and there is no known treatment, in large part due to the lack of appropriate preclinical disease models in which to test therapies. Notably, expression of Kir6.1 and SUR2 does not fully overlap, and the relative contribution of K$_{\text{ATP}}$ GOF in various cardiovascular tissues remains to be elucidated. To investigate pathophysiologic mechanisms in CS we have used CRISPR/Cas9 engineering to introduce CS-associated SUR2[A478V] and Kir6.1[V65M] mutations to the equivalent endogenous loci in mice. Mirroring human CS, both of these animals exhibit low systemic blood pressure and dilated, compliant blood vessels, as well dramatic cardiac enlargement, the effects being more severe in V65M animals than in A478V animals. In both animals, whole-cell patch-clamp recordings reveal enhanced basal K$_{\text{ATP}}$ conductance in vascular smooth muscle, explaining vasodilation and lower blood pressure, and demonstrating a cardinal role for smooth muscle K$_{\text{ATP}}$ dysfunction in CS etiology. Echocardiography confirms in situ cardiac enlargement and increased cardiac output in both animals. Patch-clamp recordings reveal reduced ATP sensitivity of ventricular myocyte K$_{\text{ATP}}$ channels in A478V, but normal ATP sensitivity in V65M, suggesting that cardiac remodeling occurs secondary to K$_{\text{ATP}}$ overactivity outside of the heart. These SUR2[A478V] and Kir6.1[V65M] animals thus reiterate the key cardiovascular features seen in human CS. They establish the molecular basis of the pathophysiological consequences of reduced smooth muscle excitability resulting from SUR2/Kir6.1-dependent K$_{\text{ATP}}$ GOF, and provide a validated animal model in which to examine potential therapeutic approaches to treating CS.

Introduction

Cantu syndrome (CS) was first recognized as a distinct pathology 35 years ago (1). The syndrome is extremely complex, with patients typically demonstrating a host of cardiovascular features including marked cardiomegaly, vascular dilation and tortuosity, low blood pressure, persistence of fetal circulation, and pulmonary hypertension (2–6), in addition to hypertrichosis and acromegaloid facial features (7, 8). The molecular basis is now clear: CS results from mutations in the $ABCC9$ and $KCNJ8$ genes, which encode the regulatory $ABCC9$ (SUR2) sulfonylurea receptor and pore-forming $KCNJ8$ (Kir6.1) subunits, respectively, of ATP-sensitive potassium (K$_{\text{ATP}}$) channels (9–12). Expressed in various tissues in the body, K$_{\text{ATP}}$ channels are nucleotide-gated, potassium-selective channels that couple cellular metabolism to electrical excitability. $KCNJ8$ and $ABCC9$ are adjacent genes on human chromosome 12p12.1, and there is a paralogous pair of genes ($KCNJ11$ [Kir6.2] and $ABCC8$ [SUR1]) on chromosome 11p15.1, with the consequence that multiple subunit combinations may be present in K$_{\text{ATP}}$ channels in different tissues. Heterogeneity is further increased by the existence of variably spliced SUR isoforms; particularly prominent are 2 major splice isoforms of SUR2: SUR2A and SUR2B (13–15). K$_{\text{ATP}}$ channels in vascular smooth muscle are predominantly formed of Kir6.1 and SUR2B, and regulate vascular tone and blood pressure (16, 17), whereas Kir6.2 and SUR2A predominate in cardiac ventricular myocytes, wherein channel activation can result in...
significant shortening of the ventricular action potential, which may be cardioprotective in conditions of metabolic or ischemic stress (18, 19).

All identified Kir6.1 and SUR2 CS mutations result in enhanced activity of recombinant K\textsubscript{ATP} channels (20–23) and are therefore expected to result in K\textsubscript{ATP} GOF in vivo, although this has not been established. Channel GOF is in turn predicted to result in hyperpolarization of the membrane potential and thus a primary decrease of excitability, in all relevant cell types. In smooth muscle, decreased excitability would be predicted to cause vasorelaxation and lowering of blood pressure. In the myocardium, the naive prediction of K\textsubscript{ATP} overactivity would be reduced action potential duration, shortening of the QT interval, and reduced contractility as a consequence. How K\textsubscript{ATP} overactivity results in the complex and diverse pathophysiology of CS is not trivially obvious and remains largely unexplained. Here, we report the generation of CRISPR/Cas9–modified mice in which CS-associated mutations were introduced into native KCNJ8 and ABCC9 loci. These animals establish that both primary and secondary cardiovascular features of CS specifically arise from consequences of GOF missense mutations in Kir6.1 and SUR2, and inform the consequences of vascular smooth muscle inexcitability more generally.

Results

Generation of CRISPR/Cas9–modified KCNJ8- and ABCC9-mutant mice. CS arises from GOF mutations in KCNJ8 and ABCC9, the genes encoding the K\textsubscript{ATP} channel subunits, Kir6.1 and SUR2, respectively. CRISPR/Cas9 gene editing was used to introduce single-nucleotide mutations into the endogenous KCNJ8 and ABCC9 gene loci, resulting in protein substitutions that are analogous to Kir6.1\[V65M\] (V65M in mouse sequence) and SUR2\[A478V\] (A476V in mouse sequence) in human CS patients (Figure 1, A and B; see Methods).

Founder animals were all viable and fertile, and were bred back to C57BL/6J WT mice to establish several heterozygous lines of each genotype. Homozygous and heterozygous animals from generations F3 onwards were analyzed in all experiments below. There was a minor decrease in survival for heterozygous Kir6.1\[V65M\] (Kir6.1\textsubscript{wt/VM}), heterozygous SUR2\[A478V\] mice (SUR2\textsubscript{wt/AV}), and homozygous SUR2\[A478V\] (SUR2\textsubscript{AV/AV}) mice (Figure 1C). Crossing heterozygous animals from the 2 mutant lines also yielded double-heterozygous Kir6.1\textsubscript{wt/VM}/SUR2\textsubscript{wt/AV} mice, which showed markedly increased mortality (Figure 1C). Survival was drastically decreased in homozygous Kir6.1\textsubscript{V65M/VM} mice (Figure 1C), which consistently lost weight prior to dying, within a week or so after weaning (Figure 1D). Autopsy of Kir6.1\textsubscript{V65M/VM} mice sacrificed at 3 weeks...
of age revealed distended intestines which, when considered alongside the observed weight loss, may indicate impaired gastrointestinal function.

Mutation of Kir6.1 and SUR2 results in GOF of native vascular smooth muscle KATP channels, but ventricular myocyte KATP is only affected in SUR2-mutant mice. The effects of the introduced mutations on KATP channel function were determined using patch-clamp electrophysiology. Firstly, whole-cell patch-clamp recordings, using an intracellular pipette solution containing no ATP (see Methods), revealed a markedly higher (~5-fold) basal potassium conductance in acutely isolated aortic smooth muscle cells from Kir6.1wt/VM mice, compared with WT (Figure 2, A and C). Application of the KATP channel opener, pinacidil, provoked significant increase in conductance in WT vascular smooth muscle cells (VSMCs), but this effect was blunted in VSMCs from V65M mice, reflecting basal activation of the mutant KATP channels. Subsequent application of the KATP channel inhibitor, glibenclamide, markedly reduced the pinacidil-activated conductance in WT VSMCs, but was less effective in V65M (Figure 2, A and C), potentially reflecting the reduced glibenclamide sensitivity of Kir6.1[V65M] channels (21). Importantly, inclusion of a high concentration (5 mM) of ATP in the patch pipette essentially abolished both basal and pinacidil-activated conductances in cells from both WT and V65M VSMCs (Figure 2, B and C), confirming that the observed conductances resulted from KATP channel activity.

Because homozygous SUR2AV/AV mice survive to adulthood, we were able to analyze the effect of the SUR2[A478V] mutation in both heterozygous SUR2wt/AV and homozygous SUR2AV/AV mice. In both
cases, basal $K_{ATP}$ activation was also increased in whole-cell patch-clamp recordings from isolated VSMCs (~1.5-fold and ~2.2-fold increases for SUR2$^{wt/AV}$ and SUR2$^{AV/AV}$, respectively) (Figure 2, D and E). Glibenclamide reduced currents to near basal levels and, again, inclusion of 5 mM ATP in the pipette solution abolished basal K$^+$ conductances (Figure 2E), confirming that the increase observed in SUR2$^{A478V}$ VSMCs was due to elevated basal K$_{ATP}$ activity. Notably, the K$_{ATP}$ GOF in VSMCs from both SUR2$^{wt/AV}$ and SUR2$^{AV/AV}$ mice was less than that observed in Kir6.1$^{wt/VM}$ mice, which is consistent with the effect of these 2 substitutions in recombinantly expressed K$_{ATP}$ channels (21, 24).

Nucleotide regulation of native K$_{ATP}$ channels in the heart was assessed using excised, inside-out patch-clamp recordings from acutely dissociated ventricular myocytes. Consistent with the prevailing evidence that ventricular K$_{ATP}$ channels are composed predominantly of Kir6.2/SUR2A subunits (i.e., that Kir6.1 is not present in these channels), there was no difference between sensitivity of WT or V65M channel activity to MgATP (Figure 3, A and B), which provides a combined assessment of ATP inhibition and Mg-nucleotide activation of channels. In contrast, excised patch-clamp recordings from SUR2$^{wt/AV}$ and SUR2$^{AV/AV}$ ventricular myocytes revealed right-shifted MgATP sensitivity (~2- and ~3.5-fold increases in IC$_{50}$, respectively; Figure 3, C and D), as predicted, given that SUR2 is expressed in ventricular myocytes (15). Thus, in both VSMCs and ventricular myocytes a progressive increase in GOF was observed through heterozygous and homozygous SUR2$^{A478V}$ mice. Taken together, these data confirm the expected molecular consequences of the Kir6.1$^{V65M}$ substitution, i.e., that it results in marked GOF of ventricular K$_{ATP}$ channels, whereas the SUR2$^{A478V}$ substitution results in GOF of K$_{ATP}$ channels in both VSMCs and ventricular myocytes.

We subsequently analyzed cellular, organelle, and whole-animal phenotypes of the different genotypes. Despite the above qualitatively different outcomes for ventricular K$_{ATP}$ properties in the Kir6.1$^{V65M}$ and SUR2$^{A478V}$ animals, all of the subsequent features described below were qualitatively similar in
both Kir6.1[V65M] and SUR2[A478V] animals, but they were more marked in the former. Therefore, we first present in detail the findings from Kir6.1[V65M] animals, and then present parallel data from the SUR2[A478V] animals.

Vascular consequences of $K_{ATP}$ GOF. CS patients exhibit dilated and tortuous blood vessels, reduced blood pressure, and decreased pulse wave-velocity (4, 25), suggestive of a chronically relaxed, compliant vasculature. In Kir6.1[wt/VM] mice, marked changes in gross vascular structure were observed, including significantly increased aortic diameters (ranging from ~15% to 70% increases around the proximal aorta, not significant at the aortic arch), as measured in vivo by echocardiographic imaging and directly on isolated tissue (Figure 4A). Assessment of pressurized carotid arteries, reflecting noncontractile biomechanical properties of the vessels, revealed significantly increased arterial diameters across the full range of physiological pressures, and increased compliance (Figure 4B).

Marked reduction (~20–25 mmHg) of both systolic and diastolic basal blood pressures were observed in anesthetized 3-month-old Kir6.1[wt/VM] mice (Figure 4C). Acute administration of pinacidil, which reduces
blood pressure by activation of smooth muscle $K_{ATP}$ in WT mice, was severely blunted in Kir6.1wt/VM animals (Figure 4, C and D), reflective of the high basal $K_{ATP}$ activity and consequently reduced additional activation by pinacidil that is seen in isolated VSMCs (Figure 2). In agreement with data from the anesthetized mice, ambulatory telemetric recordings also showed approximately 30-mmHg decreases in blood pressure in Kir6.1wt/VM mice at both night and day, although the difference was not significant during the daytime (Figure 4E). Therefore, Kir6.1wt/VM mice display dilated, compliant arterial vessels resulting in hypotension, mirroring clinical observations in CS patients (4, 25).

**Cardiac hypertrophy in Cantu mice.** Cardiomegaly is a consistent finding in CS patients (25) and is dramatically recapitulated in adult Kir6.1wt/VM mice, which show approximately 1.7-fold increases in heart weight (Figure 5A). Estimates of ventricular myocyte size, both from cell capacitance, a correlate of cell membrane surface area, in whole-cell voltage-clamp recordings of isolated myocytes (n = 11 for WT and 16 for Kir6.1wt/VM), and from measurements of cell surface area (CSA) from H&E-stained ventricular tissue (n = 116 cells from 3 mice for WT and 69 cells from 3 mice for Kir6.1wt/VM), Parasternal long-axis echocardiographic imaging shows increased left ventricle (LV) internal diameter and wall thickness in Kir6.1wt/VM (endo- and epicardial boundaries indicated by white or blue lines for WT and Kir6.1wt/VM, respectively). Echocardiographic imaging in vivo also demonstrates an approximately 2-fold increase in left ventricle (LV) mass in Kir6.1wt/VM mice, with dilated LV chamber diameters (~30% increase) along with approximately equivalent increases in LV posterior wall and intraventricular septal thickness, compared...
with WT (Figure 5, D and E). Consequently, relative wall thickness (RWT) was not significantly different in Kir6.1 wt/VM mice (RWT for WT 0.57 ± 0.02 mm; for Kir6.1 wt/VM 0.52 ± 0.03 mm; \( P = 0.1 \)), although suggestive of a mild prevailing eccentric hypertrophy.

Therefore, despite Kir6.1 wt/VM cardiac myocytes showing essentially normal \( K_{ATP} \) channels, Kir6.1 wt/VM hearts display chamber dilation and marked cardiac enlargement as a result of cellular hypertrophy, again consistent with echocardiographic findings in CS patients (3, 25).

**Aortic regurgitation and stenosis in Kir6.1 wt/VM mice.** Cardiac hypertrophy can be associated with valvular defects and/or aortic insufficiency (AI), as has been reported in CS patients (2, 6). Aortic valve function was assessed in vivo by echocardiography. AI and aortic stenosis (AS) of variable extent were observed in 4 of 5 Kir6.1 wt/VM mice, with 0 of 5 WT littermate controls affected (Figure 6, A and B). The extent of AI was strongly correlated with the measured aortic diameter (sinotubular junction diameter, Figure 6C). In addition, relative AS was apparent in 4 of 5 Kir6.1 wt/VM mice, in which qualitative valve thickening and restricted leaflet opening were observed (Figure 6, A and B). This was accompanied by elevated mean pressure gradients across the valve in the Kir6.1 wt/VM mice (Figure 6, A and B, and Supplemental Video 1; supplemental material available online with this article; https://doi.org/10.1172/jci.insight.121153DS1).

This combination of AI and increased preload, alongside stenotic or dysfunctional valves with resultant increases in afterload, could contribute to the LV hypertrophy and chamber dilation that are observed. However, there was only a weak correlation between AI or mean gradient and LV mass (Figure 6C), suggesting that both AI and valvular defects may not be primary drivers of hypertrophy in these mice.

**Increased cardiac output in Kir6.1 wt/VM mice.** In echocardiographic recordings, fractional shortening was not different from WT, but cardiac output was dramatically (~65%) higher, due to equivalently greater stroke volume (Figure 7, A–E). There was a significantly (~80%) higher rate of LV emptying (dV/dT max)
in Kir6.1wt/VM mice (Figure 7F). This combination of features is consistent with the characteristic high-output cardiac phenotype observed in CS patients (25) that is distinct from typical hypertrophic or dilated cardiomyopathies in which systolic function is impaired. It is consistent with earlier studies of transgenic mice, which showed that expression of KATP GOF subunits in either the myocardium or in VSM both result in hypercontractile phenotypes in the heart (25, 26). These outcomes are not directly predicted from any expected electrophysiological consequences of cardiac KATP channel GOF. Baseline surface ECG recordings from ambulatory Kir6.1wt/VM mice were not markedly different from WT, consistent with patch-clamp studies of isolated ventricular myocytes showing no major changes in Kir6.1 wt/VM cardiac KATP function (Figure 3). Therefore, we suggest that the high-output, enlarged heart observed in Kir6.1 wt/VM mice may result not from a primary effect on cardiac K_{ATP} but rather from systemic feedback mechanisms that counter hypotension arising from vascular K_{ATP} GOF.

Key CS features are common to both Kir6.1 and SUR2 GOF mutant mice. Basal systolic and diastolic blood pressures were also decreased relative to WT, in both anesthetized SUR2^{AV/AV} and SUR2^{wt/AV} mice. Ambulatory blood pressures also decreased in both, but only significantly so in SUR2^{AV/AV} mice (Figure 8, A and B). As seen in Kir6.1[V65M] animals, the relative blood pressure-lowering effect of pinacidil was again reduced in SUR2^{wt/AV}, and more so in SUR2^{AV/AV} (Figure 8, A and C), to the extent that, intriguingly, the lowest pressure achieved with pinacidil was actually higher in SUR2^{wt/AV} than WT, and even more so in SUR2^{AV/AV} (Figure 8, A and C), the implications of which are considered in the Discussion. As observed in Kir6.1wt/VM mice, there were clear trends towards progressively increased vascular...
diameters, both in vivo in echocardiographic imaging and ex vivo in pressurized compliance measurements on isolated vessels, for SUR2wt/AV and SUR2AV/AV mice (Figure 8, D–F).

Marked cardiomegaly was also observed in both SUR2wt/AV and SUR2AV/AV mice (~1.2- and ~1.6-fold increases, respectively; Figure 9A), which cell surface area measurements again revealed to result from cellular hypertrophy (Figure 9B). Again, echocardiographic measurements revealed maintained fractional shortening, despite LV dilation, while cardiac output and stroke volume were significantly increased (Figure 9, C–E).

Discussion

**The pathophysiological effects of K\(_{\text{ATP}}\) GOF in CS.** Autosomal dominant GOF mutations in KCNJ8 and ABCC9, the genes encoding the Kir6.1 and SUR2 subunits of K\(_{\text{ATP}}\) potassium channels, have now been established as the genetic basis of CS (20–24, 27). In addition to hypertrichosis and coarse facial appearance, CS patients are characterized by a constellation of cardiovascular features, including marked cardiomegaly, vascular dilation and tortuosity, low blood pressure, persistence of fetal circulation, and pulmonary hypertension (2–6). While low blood pressure is a directly predictable primary consequence of vascular K\(_{\text{ATP}}\) GOF (Figure 10A), few of the other features, particularly the cardiac enlargement, have a ready explanation, and no direct causal association between the genetic basis and these outcomes has been established.
In generating animal models in which specific CS mutations are introduced into the equivalent endogenous loci in the mouse genome, we can therefore directly test the causal association. The above studies demonstrate that CS-associated GOF substitutions in both Kir6.1 and SUR2 cause a common constellation of complex cardiovascular features, including increased vascular dilation and compliance, low blood pressure, cardiac hypertrophy, and increased cardiac output. As such, our mouse models recapitulate the key cardiovascular features observed clinically in CS (2, 3, 6). We observe a clear correlation between the extent of basal vascular KATP channel activation and the severity of cardiovascular abnormalities through SUR2wt/AV, SUR2AV/AV, and Kir6.1wt/VM mice (Figure 10B). Notably, this phenotypic severity also correlates with the previously reported biophysical effects of these mutations (21, 22, 24). In the compound heterozygous Kir6.1wt/VM/SUR2wt/AV and homozygous Kir6.1V/V animals, the presumably even stronger molecular phenotype results in early death. This precluded detailed assessment of cardiovascular outcomes, but revealed what may be lethal effects of resultant gastrointestinal insufficiency. Interestingly, human CS is likely to represent a more severe clinical categorization within a spectrum of Kir6.1/SUR2 GOF–associated disorders that also includes acromegaloid facial appearance (AFA) syndrome and hypertrichosis with acromegaloid facial features (HAFF) syndrome, in which cardiovascular abnormalities are not reported (28). The severity of human disease may directly correlate with effects on molecular function but some of the same mutations have been reported in both CS and AFA/HAFF patients, so drawing quantitative phenotype-to-genotype comparisons may prove difficult and will require more detailed investigation of multiple mutations (20, 27–29).

Vascular consequences of KATP GOF — primary CS pathological consequences. That deliberate introduction of these GOF mutations in both ABCC9 and KCNJ8 genes converge to the same pathophysiology conclusively demonstrates that the associated pathologies, as observed in CS, result from changes in the KATP channel complex that is generated by SUR2 and Kir6.1 protein association (5, 22). It further indicates that the primary consequences must arise in tissue(s) in which Kir6.1 and SUR2 are expressed. Kir6.1 and SUR2 are clearly both expressed in VSMCs (15, 30), but the situation in cardiac myocytes...
Most studies indicate that SUR2 is the primary sulfonylurea receptor in the ventricle, and that Kir6.2 is the pore-forming subunit (31), evidence for Kir6.1 expression being mostly limited to isolated reports of expression in conducting tissue (32). That the most severe CS features are present in Kir6.1[V65M] mutant mice — in which KATP GOF is observed in VSMCs but not ventricular myocytes — therefore points to a cardinal role for a non–cardiac muscle origin of the ensuing pathophysiology.

Increased KATP activity in vascular smooth muscle is predicted to decrease cellular excitability and contractility. Consistent with this, SUR2-selective KATP openers acutely decrease vascular tone and lower blood pressure in WT animals (33). Enhanced basal vascular KATP activation, as was present in VSMCs from both Kir6.1[V65M] and SUR2[A478V] animals, would thus directly lead to reduced vessel contractility, explaining the lowered blood pressure and reduced response to pinacidil in the whole animal. In SUR2[A478V] animals, the maximum KATP overactivity in pinacidil is greater than WT in heterozygous and greatest in homozygous animals, yet the blood pressure in the presence of pinacidil is actually lowest in WT and highest in homozygous animals (Figure 8), counter to naive expectations.

In addition, we see that passive vessel compliance is increased in both genotypes. Increased vessel compliance may reflect increased elastin production in smooth muscle, as has been reported in response to pharmacological activators of KATP channels in cultured smooth muscle cells (34), and in the rat aorta (35).

It should be noted that endothelial KATP channels have also been implicated in blood pressure control (36, 37), and in angiogenesis (38–40). Thus, endothelial dysfunction may also contribute to decreased vascular tone and vessel tortuosity in CS, but this remains to be fully elucidated.

AS, AI, and valvular defects are also reported in association with human CS (2, 6). Here we demonstrate functional defects in the aortic valve of Kir6.1[wt/VM] mice alongside AI and apparent aortic valve stenosis. As extensive dilation is observed throughout the vasculature in CS patients (4), and in the Cantu mice, we hypothesize that AI may be a direct consequence of aortic root dilation. Consistent with this, there is a marked correlation between aortic diameter and AI in Kir6.1[wt/VM] mice. The complex combination of

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Figure 10. Progressive cardiovascular consequences of Cantu syndrome. (A) The primary consequence of KATP GOF in the vasculature is reduced excitability, leading to functional and structural vasodilation, low blood pressure, and underperfusion. Secondly, this leads to a compensatory cardiac hypertrophy and hypercontractility. (B) These features are present in even mild (e.g., SUR2[wt/m]) CS models, but are exacerbated in more severe genotypes (e.g., Kir6.1[wt/m] and SUR2[wt/m]). The latter genotypes are associated with premature death, and very early death occurs immediately after weaning in the most severe genotypes (e.g., SUR2[wt/m]/Kir6.1[wt/m] and Kir6.1[wt/m]).
mutually exacerbating AI and AS would be predicted to increase LV preload and afterload, respectively, and thence to increase cardiac hypertrophy (see below).

**Structural and electrical remodeling in the heart — secondary consequences of K$_{ATP}$ GOF.** In contrast to the observed vascular manifestations, there are no ready explanations to link K$_{ATP}$ GOF and the cardiac features of CS. The naive expectation of K$_{ATP}$ GOF in the heart itself would be action potential shortening, or slowing of the cardiac rate, either or both of which will lead to net reduction in cardiac output. However, in CS patients (25), and in both Kir6.1[V65M] (Figure 5) and SUR2[A478V] (Figure 9) mutant mice, we observe profound cardiac enlargement and enhanced cardiac output. This is despite the different effects of the Kir6.1 and SUR2 mutations on ventricular K$_{ATP}$ channel properties (Figure 3). Hence we suggest that cardiac enlargement is likely to predominantly arise independently of ventricular K$_{ATP}$ activity, and to instead be a secondary consequence of vascular dysfunction (Figure 10A). The enlargement observed in the Cantu hearts includes increased LV internal dimensions and wall thickness. This combination is distinct from typical eccentric or concentric hypertrophies arising from volume or pressure overload, respectively, and functionally resembles physiological, exercise-induced, hypertrophy, in which fractional shortening is maintained (41).

**Long-term effects of CS pathophysiology and implications.** The CS combination of cardiac cellular hypertrophy, with chamber and wall enlargement, AI, enhanced cardiac contractility, together with vascular dilation and low blood pressure may represent a unique pathophysiological constellation, distinct from other commonly defined conditions of myocardial hypertrophy. Little is yet known about the progressive nature of CS, but it is notable that the majority of diagnosed patients are children or young adults. Whether this reflects the recent recognition of the condition itself (the genetic basis was only discovered in the last 6 years) and the success of modern palliative therapies, or is an indication of poor long-term prognosis, remains to be elucidated. Cardiac output is elevated in 3-month-old Cantu mice (Figures 5 and 7), but further studies will be required to determine whether the various cardiac abnormalities result in a progressive functional decline with long-term aging, such as is observed in other forms of pathological hypertrophy.

First demonstrated in mice almost 20 years ago (42), recognition of the causal role of GOF mutations in the Kir6.2/SUR1 proteins in neonatal diabetes (43) has led to dramatically improved understanding of the pathophysiological consequences (44), as well as a revolution in therapy using K$_{ATP}$ channel–blocking sulfonylurea drugs (45, 46). The Cantu mouse models we describe here will provide the opportunity for longitudinal analysis of CS pathophysiology over time, as well as an appropriate preclinical model in which to test the efficacy of K$_{ATP}$ inhibitors (such as sulfonylureas) or other potential therapies, for what is currently an untreatable syndrome. Moreover, as these mice now confirm a causal link between K$_{ATP}$ GOF mutations and a host of complex cardiovascular outcomes, they point the way to future studies aimed at understanding the broader consequences of pathophysiological changes in K$_{ATP}$ channel resulting from nongenetic causes, such as altered cell signaling.

**Methods**

**Study approval**

Studies were performed in compliance with the standards for the care and use of animal subjects defined in the NIH Guide for the Care and Use of Laboratory Animals (33) and were reviewed and approved by the Washington University Institutional Animal Care and Use Committee.

**CRISPR/Cas9 genome editing**

Using CRISPR/Cas9–mediated genome engineering technology (47), we generated knockin mice carrying human GOF mutations in the ABCC9 or KCNJ8 genes, which encode the accessory SUR2 and the pore-forming Kir6.1 subunits of the K$_{ATP}$ channel, respectively. The guide RNA (gRNA) target sequences were predicted using the MIT CRISPR design tool (http://crispr.mit.edu). abcc9 gRNA (5′ CATTGCCACGAAGCTGGCGG 3′) or kcnj8 gRNA (5′ ACGCCACTTCAGGCTTACCA 3′) were subcloned into BbsI-digested plasmid pX330 (Addgene, 42230). sgRNA activity was validated in vitro by transfection of N2A cells using Roche Xtremegene HP , followed by T7E1 assay (NEB). T7 sgRNA template and T7 Cas9 template were prepared by PCR amplification and gel purification, followed by RNA in vitro transcription with the MEGAshortscript T7 kit (gRNA) or the T7 mMessage mMachine Ultra kit (Cas9). After transcription, RNA was purified with the Megaclear kit (Life Technologies). Single-stranded oligodeoxynucleotide (ssODN) donor DNAs (200 nt) with the appropriate mutation centered within the ODN were synthesized by IDT as ultramer ODNs.
B6CBA F1/J female mice (3–4 weeks old; Jackson Laboratory) were superovulated and mated overnight with B6CBA F1/J male mice (>7 weeks old). Zygotes were harvested from the ampullae of superovulated females and placed in potassium-supplemented simplex optimized medium (KSOM; MR106D) before microinjection. Microinjection of the Cas9, sgRNA, and ssDNA template (at a final concentration of 50 ng/μl Cas9 WT RNA, 25 ng/μl gRNA, and 20 ng/μl ssODN DNA) was performed in flushing holding medium (FHM; MR-024-D; EmbryoMax; Millipore). After injection, zygotes were incubated at 5.5% CO2 at 37°C for 2 hours, and surviving embryos were transferred to ICR recipient mice by oviduct transfer. Founders were identified using Qiagen pyrosequencer and Pyromark Q96 2.5.7 software. We identified 12 positive founder animals carrying CS mutation mouse SUR2[A476V] (equivalent to human SUR2[A478V]), and 2 positive founder animals carrying the CS mutation Kir6.1[V65M]. All founders were viable and fertile. Successful mutation of founder (F0) mice was verified by Sanger sequencing of genomic DNA and mutant mice were subsequently crossed with C57BL/6J mice to generate heterozygous F1 Kir6.1wt/VM and SUR2 wt/AV lines. PCR was used to generate amplicons of KCNJ8 and ABCC9 spanning >1 kb on either side of the introduced mutation, from gDNA isolated from mouse tails, and resultant PCR products were sequenced to confirm absence of unintended additional mutations. After verification, one F1 animal from one line of each genotype was selected and further crossed against C57BL/6J to generate F2 heterozygous animals, which were intercrossed to generate F3 heterozygous and heterozygous as well as WT littermates that were used in experiments.

**Patch-clamp electrophysiology**

*Isolated VSMCs.* Mice were anesthetized with 2.5% avertin (10 ml/kg, i.p.; Sigma-Aldrich) and the descending aorta was rapidly dissected and placed in ice-cold physiological saline solution (PSS) containing (in mM) 134 NaCl, 6 KCl, 2 CaCl2, 1 MgCl2, 10 HEPES, and 10 glucose, with pH adjusted to 7.4 with NaOH. Smooth muscle cells were enzymatically dissociated in dissociation solution containing (in mM) 55 NaCl, 80 sodium glutamate, 5.6 KCl, 2 MgCl2, 10 HEPES, and 10 glucose, pH 7.3 with NaOH, then placed into dissociation solution containing papain μg/ml 12.5, 1 mg/ml dithioerythritol, and 1 mg/ml BSA for 25 minutes (at 37°C), before transfer to dissociation solution containing 1 mg/ml collagenase (type H/F = 1:2), and 1 mg/ml BSA for 5 minutes (at 37°C). Cells were dispersed by gentle trituration using a Pasteur pipette, plated onto glass coverslips on ice, and allowed to adhere for more than 1 hour before transfer to the recording chamber.

Whole-cell KATP currents were recorded using an Axopatch 200B amplifier and Digidata 1200 (Molecular Devices). Recordings were sampled at 3 kHz and filtered at 1 kHz. Currents were initially measured at a holding potential of ~70 mV in a high-Na+ bath solution containing (in mM) 136 NaCl, 6 KCl, 2 CaCl2, 1 MgCl2, 10 HEPES, and 10 glucose, with pH adjusted to 7.4 with NaOH before switching to a high-K+ bath solution (140 KCl, 2 CaCl2, 1 MgCl2, 10 HEPES, and 10 glucose, with pH adjusted to 7.4 with KOH) in the absence and presence of pinacidil and glibenclamide as indicated. The pipette solution contained (in mM) 110 potassium aspartate, 30 KCl, 1 MgCl2, 10 HEPES, 0.5 CaCl2, 4 K2HPO4, and 5 EGTA, with pH adjusted to 7.2 with KOH.

*Isolated ventricular myocytes.* Adult mice were anesthetized using 2.5% Avertin (10 ml/kg), and the heart and ascending aorta were removed and immersed in ice-cold calcium-free Wittenberg Isolation Medium (WIM; in mM): 116 NaCl, 5.4 KCl, 8 MgCl2, 1 NaH2PO4, 1.5 KH2PO4, 4 NaHCO3, 12 glucose, 21 HEPES, 2 glutamine plus essential vitamins (GIBCO), and essential amino acids (GIBCO) (pH 7.40). The heart was cannulated via the aorta and Langendorff perfused with WIM for 5 minutes at 37°C, followed by 20-minute perfusion of WIM supplemented with 270 units/ml of collagenase type 2 (Worthington Biochemical) and 10 μM CaCl2 at 37°C. The heart was then transferred to WIM containing 50 mg/ml BSA, 12.5 mg/ml taurine, and 150 μM CaCl2, and ventricular tissue was manually dissociated using forceps before single-cell dissociation by trituration with a fire-polished Pasteur pipette.

Inside-out patch-clamp recordings were made in symmetrical KINT solution that contained (in mM) 140 KCl, 10 HEPES, 1 EGTA (pH 7.4 with KOH). Varying MgATP concentrations were applied using a Dynaflow Resolve perfusion chip (Celletricon). MgCl2 was added to each solution to achieve a free [Mg2+] of 0.5 mM according to calculations using CaBuf (Katholieke Universiteit Leuven). Membrane currents were sampled at 3 kHz, filtered at 1 kHz, at a holding potential of ~50 mV using an Axopatch 700B amplifier and Digidata 1200. KATP channel currents in solutions of varying nucleotide concentrations...
were normalized to the basal current in the absence of nucleotides and dose-response data were fit with a 4-parameter Hill fit according to the equation: Normalized current = \( I_{\text{min}} + \left( I_{\text{max}} - I_{\text{min}} \right) / (1 + ([X] / IC_{50})^H) \), where the current in \( K_{\text{int}} = I_{\text{max}} = 1 \), \( I_{\text{min}} \) is the normalized minimum current observed in MgATP, \([X]\) refers to the concentration of MgATP, \( IC_{50} \) is the concentration of half-maximal inhibition, and \( H \) denotes the Hill coefficient.

Arterial compliance

After mice were euthanized under isoflurane anesthesia, the left common carotid arteries of 3-week-old mice were excised and placed in PSS containing 130 mM NaCl, 4.7 mM KCl, 1.18 mM MgSO\(_4\)-7H\(_2\)O, 1.17 mM KH\(_2\)PO\(_4\), 14.8 mM NaHCO\(_3\), 5.5 mM dextrose, and 0.026 mM EDTA (pH 7.4). The vessels were then cleaned from surrounding fat, mounted on a pressure arteriograph (Danish Myo Technology) and maintained in PSS at 37\(^\circ\)C. Vessels were visualized with an inverted microscope connected to a charged-coupled device camera and a computerized system, which allows continuous recording of vessel diameter. Intravascular pressure was increased from 0 to 175 mmHg by 25-mmHg increments and the vessel outer diameter was recorded at each step (12 seconds per step). The average of 3 measurements at each pressure was reported.

Blood pressure measurement

Mice were anesthetized with 1.5% inhaled isoflurane and restrained on a heating pad to maintain body temperature. A 2- to 3-mm incision was made in the midline of the neck; the thymus and muscle were separated to expose the right carotid artery. A Millar pressure transducer (model SPR-671) was carefully inserted into the right carotid artery and moved to the ascending aorta. Systolic blood pressure, diastolic blood pressure, and heart rate were recorded using the PowerLab data acquisition system (ADInstruments), and data were analyzed using LabChart 7 (ADInstruments). For blood pressure measurements in conscious mice, a radio-telemetry pressure transmitter (Data Science International, DSI) was surgically inserted into the left carotid artery and moved to the ascending aorta, where blood pressures in day and night were recorded by DSI data acquisition system after mice recovered from surgery.

Heart weight measurement and histology

Mice were anesthetized with 2.5% Avertin and hearts were excised and rinsed with PBS that contained (in mM) 137 NaCl, 2.7 KCl, 10 Na\(_2\)HPO\(_4\), and KH\(_2\)PO\(_4\) (pH 7.4 with NaOH). The hearts were arrested in diastole with 10% KCl, and blotted to remove excess liquid. Hearts were then weighed and weight was normalized to tibia length. After weighing, the hearts were fixed in 10% buffered formalin for 24 hours, and embedded in paraffin. Sections (3 \(\mu\)m) were cut and stained with H&E for the morphometric analysis.

Echocardiography

Echocardiography was performed using a Vevo 2100 Imaging System (VisualSonics) equipped with a 30-MHz linear-array transducer according to previously published methods (48–50). Cardiac images were obtained by a handheld technique using 100 mg/kg i.p. tribromoethanol anesthetic; aortic images were obtained under 1.5% inhaled isoflurane. M-mode images were used to make LV dimensional measurements. Quantitative image analysis was also performed using a speckle-tracking algorithm to obtain volumetric and strain data. Sagittal 2D images of the aortic arch were used to measure aortic diameters at multiple levels and to obtain Doppler images for pulse wave velocity measurements.

Statistics

Unless otherwise noted, data were tested for statistical significance using \( t \) test or multiway ANOVA with Bonferroni’s correction as applicable, and are presented as mean ± SEM. Unless otherwise noted, significance is denoted as \( P < 0.05 \).

Author contributions

YH, CM, MSR, and CGN conceived the study. YH, CM, TMH, KH, CMH, SJM, HZ, GSB, and AK carried out the experiments. RPM and SKE contributed key technical help. YH, CM, MSR, and CGN wrote the manuscript, which was edited by the other authors.
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