Agonist-Induced Hypertrophy and Diastolic Dysfunction Is Associated with Selective Reduction in Glucose Oxidation: A Metabolic Contribution to Heart Failure with Normal Ejection Fraction

Mori et al: Glucose Oxidation and Diastolic Dysfunction

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Abstract

Background—Activation of the renin-angiotensin and sympathetic nervous systems may alter cardiac energy substrate preference thereby contributing to the progression of heart failure with preserved ejection fraction. We assessed the qualitative and quantitative effects of Ang II and the $\alpha$-adrenergic agonist, phenylephrine (PE), on cardiac energy metabolism in experimental models of hypertrophy and diastolic dysfunction and the role of the AT1R.

Methods and Results—Ang II (1.5 mg.kg$^{-1}$.d$^{-1}$) or PE (40 mg.kg$^{-1}$.d$^{-1}$) was administered to 9 week-old male C57/Bl6 WT mice for 14 days via implanted micro-osmotic pumps. Echocardiography showed concentric hypertrophy and diastolic dysfunction with preserved systolic function in Ang II and PE treated mice. Ang II induced marked reduction in cardiac glucose oxidation and lactate oxidation with no change in glycolysis and fatty acid $\beta$-oxidation. TCA acetyl CoA production and ATP production were reduced in response to Ang II. Cardiac pyruvate dehydrogenase kinase 4 (PDK4) expression was upregulated by Ang II and PE resulting in reduction in pyruvate dehydrogenase activity, the rate-limiting step for carbohydrate oxidation. PDK4 up-regulation correlated with activation of the cyclin/CDK-pRB-E2F pathway in response to Ang II. AT1R blockade normalized activation of the cyclin/CDK-pRB-E2F pathway, prevented the reduction in glucose oxidation but increased fatty acid oxidation.

Conclusions—Ang II and PE induced diastolic dysfunction is associated with reduced glucose oxidation due to cyclin/CDK-pRB-E2F induced upregulation of PDK4 and targeting these pathways may provide novel therapy for heart failure with normal ejection fraction.

Key Words: angiotensin II, phenylephrine, diastolic dysfunction, cardiac metabolism, pyruvate dehydrogenase 4, heart failure
The renin-angiotensin system (RAS) is known to play a key role in cardiac hypertrophy and heart failure (HF) and RAS blockade is effective in animal models and patients with cardiac hypertrophy and HF.\textsuperscript{1, 2} Ang II, a major bioactive effector of the RAS, is aberrantly activated in heart disease and plays a key role in pathological remodeling and HF.\textsuperscript{3, 4} Activation of the sympathetic nervous system and stimulation of \( \alpha \)-adrenergic receptors are also key mediators of pathological remodeling and HF progression.\textsuperscript{5} Pathological hypertrophy with diastolic dysfunction is the hallmark feature of HF with normal ejection fraction (HFNEF), a condition with adverse outcomes for which there is no approved therapies.\textsuperscript{6-9}

Heart failure induces perturbation in cardiac energy metabolism,\textsuperscript{10, 11} with mitochondrial oxidation (fatty acid oxidation and glucose oxidation) eventually becoming decreased in advanced HF.\textsuperscript{12} Ang II is involved in the regulation of cardiac metabolism. Ang II (and its precursor angiotensinogen) has been shown to decrease fatty acid oxidation rates and reduce expression of PPAR isoforms,\textsuperscript{13, 14} and also induces membrane translocation of glucose transporter 4 (GLUT-4) and increasing glucose utilization accompanied by down-regulation of AMPK.\textsuperscript{15} Glucose oxidation rates are controlled by the pyruvate dehydrogenase (PDH) complex, with pyruvate dehydrogenase kinase 4 (PDK4)-mediated phosphorylation and inhibition of the PDH complex being a central control mechanism. Given the key and fundamental role of ATP in myocardial relaxation,\textsuperscript{16, 17} metabolic perturbations may play a key role in Ang II-induced hypertrophy and diastolic dysfunction.

In the present study, we assessed Ang II and phenylephrine (PE)-induced alterations in
cardiac metabolism in models of pathological hypertrophy and diastolic dysfunction, and show that
Ang II and PE decrease glucose oxidation in association with an up-regulation of PDK4. Furthermore, we demonstrate that the cyclin/cyclin-dependent kinase (CDK)-pRB-E2F pathway plays a critical role in Ang II-induced alterations in cardiac metabolism. The AT1 receptor (AT1R) blocker, irbesartan, prevented the metabolic perturbations mediated by Ang II. These findings suggest that Ang II induces the reduction in carbohydrate oxidation in cardiac energy metabolism via the AT1R, and the cyclin/CDK-pRB-E2F pathway plays a critical role in Ang II-induced alterations in cardiac metabolism.

Methods

Detailed methodology is described in the Supplemental Expanded Methods section.

Experimental Animals and Protocol

Micro-osmotic pumps (model 1002, Alzet Corp, Palo Alto, Calif) were implanted subcutaneously at the dorsum of the neck to infuse a pressor dose of Ang II (1.5 mg.kg⁻¹.d⁻¹) or PE (40 mg.kg⁻¹.d⁻¹) for 14 days in 9 week-old male C57/BL6 WT mice, as previously described.¹⁸ A sub-group of Ang II-infused mice was also simultaneously treated with irbesartan, an AT1R blocker (50 mg.kg⁻¹.d⁻¹), or vehicle. The investigation conforms to the Care and Use of Laboratory Animals published by the US National Institutes of Health (NIH Publication No. 85-23, revised 1996) and to the guidelines of the Canadian Council on Animal Care.
Echocardiography and Hemodynamic Assessment

Transthoracic echocardiography was performed and analyzed in a blinded manner with a Vevo 770 high resolution imaging system equipped with a 30-MHz transducer (RMV-707B; VisualSonics, Toronto, Canada), as described previously. Invasive pressure measurements were made using the Millar system (MPVS-400, Millar Instruments, Texas) and tail-cuff systolic blood pressure was measured using the IITC Blood Pressure Monitoring Systems (IITC Life Science Blood Pressure System, Woodland Hills, CA).

Working Heart Model, Metabolic Measurements and PDH activity

Isolated working hearts were perfused with modified Krebs-Henseleit buffer containing 5mM glucose, 1.2mM palmitate, 1mM lactate, 3% albumin, and 100 μU/ml insulin. Hearts were subjected to 40 min perfusion with perfusate containing [U-14C]glucose and [9,10-3H]palmitate, or [5-3H]glucose and [U-14C]lactate. The rates of glucose oxidation and palmitate oxidation were measured by quantitative collection of 14CO2 and 3H2O from [U-14C]glucose and [9,10-3H]palmitate, respectively, and in a parallel series of heart the rates of glycolysis and lactate oxidation were measured by quantitative collection of 3H2O and 14CO2 from [5-3H]glucose and [U-14C]lactate respectively, as described previously. PDH activity was measured by a radiometric assay previously described.
TaqMan Real-Time PCR and Western Blot Analyses

Taqman RT-PCR was used to quantify mRNA expression levels using a ABI 7900 sequence detection system, as described previously. We extracted nuclear and cytoplasmic proteins and Western blot analyses were performed as described previously.

Histology

Picro-sirius red (PSR) staining was carried out as previously described and imaged and analyzed using fluorescence microscopy (Olympus IX80 and MetaMorp software).

Statistical Analysis

All data are presented as mean±SEM. Statistical analysis of the data was performed with the use of either a 2-tailed Student’s t-test or a one-way ANOVA followed by multiple comparison testing using Student Neuman-Keuls (SNK) testing when appropriate using the SPSS Statistics 19 software. A probability value <0.05 was considered significant.

Results

Ang II induces pathological hypertrophy and diastolic dysfunction via the AT1R

Two-dimensional/M-mode echocardiography and Doppler imaging was used to assess in vivo heart function. M-mode imaging and 2-dimensional short-axis mid-ventricular views revealed increased wall thickness of the LV induced by Ang II, but normal systolic function with no
statistically significant difference in fractional shortening and ejection fraction (Figure 1A-D, Supplemental Table 1). The functional abnormality in response to Ang II was characterized by diastolic dysfunction, leading to increased A-wave amplitude accompanied by the reduction of the E/A ratio, as well as tissue Doppler imaging showing reduced E’-wave amplitude resulting in the elevation of E/E’ ratio and a reduction of the E’/A’ ratio (Figure 1E-H, Supplemental Table 1). Diastolic dysfunction was confirmed by invasive hemodynamic assessment, which showed elevated LV end-diastolic pressure and reduced –dP/dt max in response to Ang II (Supplemental Table 2). Morphometric assessment and expression analysis of pathological hypertrophy markers showed increased cardiac hypertrophy in response to Ang II (Supplemental Figure 1). LV dry weight and percent LV dry weight/body weights were significantly increased in Ang II-treated mice with markedly increased expression of atrial natriuretic factor (ANF), brain natriuretic peptide (BNP), β-myosin heavy chain (β-MHC), α-skeletal actin (α-SA), and cardiomyocyte cross-sectional area (Supplemental Figure 1A-H). These results indicate that Ang II induces a hypertrophied heart with diastolic dysfunction and preserved systolic function. The pathological effects of Ang II are mediated predominantly by the AT1R.4,24 We administered irbesartan to Ang II-treated mice to assess the effects of AT1R blockade on Ang II-induced heart function and morphometric changes. Irbesartan prevented the Ang II-induced concentric hypertrophy and diastolic dysfunction (Figure 1A-H, Supplemental Tables 1 and 2), with reversal of the morphometric and molecular correlates of pathological hypertrophy (Supplemental Figure 2). These results suggest that Ang II induces pathological hypertrophy and diastolic dysfunction via
the AT1R.

**Ang II-induced alterations in cardiac energy metabolism and efficiency: effects of AT1R blockade**

Metabolic perturbations may represent a key driver of diastolic abnormalities in the setting of pathological hypertrophy.\(^{16,17,25}\) We therefore subjected hearts to *ex vivo* aerobic perfusions to measure cardiac function and rates of cardiac energy metabolism (fatty acid oxidation, glucose oxidation, lactate oxidation, and glycolysis). Overall mechanical function between vehicle and Ang II treated hearts during *ex vivo* aerobic perfusions were similar (Supplemental Table 3) which is consistent with the echocardiographic and invasive hemodynamic assessment, and collectively confirms that Ang II-treated hearts maintained normal systolic function. Ang II resulted in reduced cardiac work (Figure 2A) in association with a 45% decrease in glucose oxidation (vehicle: 946±75 nmol·g dry wt\(^{-1}\)·min\(^{-1}\); Ang II: 518±36 nmol·g dry wt\(^{-1}\)·min\(^{-1}\); p<0.05) (Figure 2B) and a 31% decrease in lactate oxidation (Figure 2C). In contrast, no statistically significant change in either palmitate oxidation (Figure 2D) or glycolysis (vehicle: 14.96±2 versus Ang II: 10.81±2.1 μmol·g dry wt\(^{-1}\)·min\(^{-1}\); p=0.32) occurred in response to Ang II. The resultant decrement in myocardial glucose and lactate oxidation lowered total acetyl CoA production (Figure 2E) and ATP production (Supplemental Table 4) in response to Ang II. These data indicated that Ang II selectively reduces carbohydrate oxidation and its contribution to tricarboxylic acid cycle activity, resulting in impaired ATP production. We next assessed the effects of AT1R blockade on these
cardiac energy perturbations. Ang II-mediated reduction in glucose oxidation and lactate oxidation were prevented by treatment with irbesartan (Figure 2B and C). In contrast, the rate of palmitate oxidation was not significantly decreased in Ang II treated hearts, and was normalized by irbesartan (Figure 2D). The reduction in total acetyl CoA production was also normalized (Figure 2E). Since cardiac work is an important determinant of oxidative metabolism, we determined whether Ang II alterations in cardiac energy metabolism are due to decreases in cardiac work by normalizing cardiac energy metabolism for differences in cardiac work (Figure 2F-H). The significant reduction in glucose oxidation in response to Ang II treatment remained when corrected for differences in cardiac work (Figure 2F). On the contrary, Ang II did not reduce either lactate oxidation or palmitate oxidation normalized for cardiac work (Figure 2G and H). Interestingly, while irbesartan normalized glucose oxidation per cardiac work (Figure 2F) in the Ang II treated hearts, both lactate and palmitate oxidation normalized for cardiac work were significantly increased above baseline values (Figure 2G and H). These results show that Ang II induces selective reduction in glucose oxidation regardless of decreases in cardiac work. Furthermore, to assess cardiac energy efficiency, we normalized cardiac work for TCA acetyl CoA production, which confirmed no statistically significant difference between vehicle-treated and Ang II-treated groups (Supplemental Table 3). Interestingly, AT1R blockade significantly decreased cardiac work per TCA acetyl CoA production. These results show that AT1R blockade induces cardiac energy inefficiency.
Ang II-induced upregulation of pyruvate dehydrogenase kinase 4 (PDK4)

We hypothesized that treatment with Ang II activates PDK4, which is the predominant PDK isoform responsible for phosphorylating and inhibiting the pyruvate dehydrogenase complex in the heart, the rate limiting enzyme for mitochondrial carbohydrate oxidation.\textsuperscript{26, 27} Western blot analysis showed cardiac expression of PDK4 protein was significantly elevated in response to Ang II (Figure 3A). In contrast, expression of PDK2 was unaltered between vehicle and Ang II-treated hearts (Supplemental Figure 3A). Active PDH activity in Ang II-treated hearts was significantly decreased (Figure 3B), but total PDH activity remained unaltered (Figure 3C), which is likely driven by increased phosphorylation of PDH (Figure 3D) in response to the up-regulation of PDK4. Consistent with a lack of change in palmitate oxidation rates, activity of $\beta$-hydroxylacyl CoA, a key enzyme of fatty acid $\beta$–oxidation, did not show significant change in response to Ang II (Supplemental Figure 3B). These results provide a mechanism for the reduction of glucose (and lactate) oxidation by Ang II in so far as Ang II-induced up-regulation of PDK4 phosphorylates and inactivates PDH, leading to reduction in carbohydrate oxidation. Consistent with restoration of glucose oxidation by AT1R blockade, PDK4 expression was decreased, resulting in up-regulation of active PDH activity (Figure 3E and F), leaving total PDH activity unchanged with decreased phospho-PDH level in response to AT1R blockade (Figure 3G and H). These results show a critical role of AT1R in mediating the Ang II-induced metabolic perturbations.
Mechanism of Ang II-induced upregulation of PDK4

Next, we explored the mechanism of Ang II-induced up-regulation of PDK4 by examining the expression of transcription factors known to modulate PDK4.\textsuperscript{28-30} The transcription factors estrogen-related receptor-\(\alpha\) (ERR\(\alpha\)) and peroxisome proliferator-activated receptor-\(\alpha\) (PPAR\(\alpha\)) positively regulate PDK4 expression. However, nuclear levels of PPAR\(\alpha\) (Supplemental Figure 3C) and ERR\(\alpha\) (Supplemental Figure 3D) were reduced in response to Ang II. The cyclin/CDK-pRB-E2F pathway is implicated in the metabolic adaptive response triggered by G-protein coupled receptor agonist and growth factors.\textsuperscript{29} Nuclear protein level of nuclear E2F1 (Figure 4A) and the expression of p-Rb (Figure 4B), an indicator of nuclear translocation of E2F1, were increased in Ang II-treated hearts. The nuclear expression of CDK4 and cytosolic expression of phospho-cyclin D1 was enhanced in Ang II treated hearts (Figure 4C and D) providing further mechanistic insight into the up-regulation of PDK4. Ang II also reduced complex I levels without affecting mitochondrial density as assessed by citrate synthase activity (Supplemental Figure 3E and F). Consistent with a key role of the cyclin/CDK-pRB-E2F pathway, increased protein expression of E2F1, phospho-Rb, CDK4, and phospho-cyclin D1 in response to Ang II were reduced by treatment with irbesartan (Figure 4E-H). Irbesartan also reversed protein expression of complex I, PPAR\(\alpha\) and ERR\(\alpha\) (Supplemental Figure 4A-C), which is likely responsible for the normalization of total acetyl CoA production (Figure 2E). These results show that the cyclin/CDK-pRB-E2F pathway is one of the possible candidates responsible for the Ang II-induced up-regulation of PDK4.
Phenylephrine-induced hypertrophy and diastolic dysfunction is associated with a selective reduction in glucose oxidation

The α₁-adrenergic agonist, phenylephrine (PE), resulted in sustained hypertension and the development of hypertrophy (Supplemental Figure 5A and B). Echocardiography revealed increased LV wall thickness with normal systolic function with no change in ejection fraction and velocity of circumferential shortening (Figure 5A and B). Phenylephrine-induced hypertrophy was associated with diastolic dysfunction, characterized by reduction of the E/A ratio, as well as tissue Doppler imaging showing reduced E’-wave amplitude thereby decreasing the E’/A’ ratio (Figure 5C-F). Metabolic assessment revealed a 50% reduction in glucose oxidation (Figure 5G), with no statistically significant difference in palmitate oxidation (Figure 5H). Consistent with the changes seen with Ang II, treatment with PE resulted in increased PDK4 and phospho-PDH levels, leading to reduced active PDH activity (Figure 5I-K). We conclude that the α-adrenergic stimulation induces concentric hypertrophy and diastolic dysfunction with selective impairment in glucose oxidation in response to increased PDK4 levels.

Discussion

Our study provides a number of important findings regarding Ang II and PE-induced alterations in cardiac energy metabolism. We demonstrate that: 1) Ang II selectively decreases glucose and lactate oxidation, 2) Ang II-induced up-regulation of PDK4 contributes to altered cardiac energy metabolism, 3) Irbesartan prevents the Ang II-induced metabolic perturbations
confirming a key role for the AT1R but increased fatty acid oxidation per unit of cardiac work, 4) the cyclin/CDK-pRB-E2F pathway plays a critical role in mediating the effects of Ang II on carbohydrate oxidation, and 5) PE selectively decreases glucose oxidation with up-regulation of PDK4. Collectively, these metabolic changes resulted in reduced cardiac efficiency in a setting of concentric pathological hypertrophy and diastolic dysfunction with preserved systolic function.

In response to Ang II and PE, active PDH activity is down-regulated. PDH activity plays a pivotal role in the development of cardiac hypertrophy, and PDH activity is down-regulated in the setting of cardiac hypertrophy. We demonstrate that PDK4 levels and phosphorylation of PDH are increased in Ang II-treated hearts. PDK4 is one of the PDK isozymes, which phosphorylates PDH and reduces the activity of PDH. Consequently, Ang II-induced reduction in carbohydrate oxidation is likely due to a decreased conversion of pyruvate to acetyl-CoA by reduction in PDH activity. Importantly, AT1R blockade using irbesartan prevents the Ang II-induced alterations in cardiac metabolism, while preventing pathological hypertrophy and diastolic dysfunction. Our results are consistent with findings in diabetic hearts where ACE inhibition reduces the expression of PDK4 and in cardiac-specific overexpression of PDK4, which results in reduced glucose oxidation.

Ang II and PE result in pathological hypertrophy with diastolic dysfunction and preserved systolic function. Ang II-induced metabolic alterations could provide a mechanistic basis for the diastolic dysfunction. Firstly, Ang II and PE reduce myocardial glucose oxidation with a relative preservation of glycolysis. While we expected the rate of glycolysis to increase, in fact the
rate of glycolysis was slightly decreased (although not significant). Ang II induces insulin resistance, and many clinical studies have shown that patients with HF have insulin resistance.\textsuperscript{35-37} As a result, it is possible that Ang II-induced insulin resistance may impair glucose uptake in the heart. Furthermore, relatively maintained fatty acid β-oxidation rates may have inhibited phosphofructokinase-1, the rate-limiting enzyme of glycolysis, thus reducing the rate of glycolysis. The resulting uncoupling between glycolysis and glucose oxidation produces protons by the hydrolysis of glycolytically derived ATP leading to intracellular acidosis. Intracellular acidosis may lead to the accumulation of intracellular Na\textsuperscript{+} due to activation of the Na\textsuperscript{+}/H\textsuperscript{+} exchanger leading to secondary elevation of intracellular Ca\textsuperscript{2+} in response to reverse mode Na\textsuperscript{+}-Ca\textsuperscript{2+} exchanger may further exacerbate the diastolic dysfunction observed in our Ang II model.\textsuperscript{38, 39} Secondly, ATP production is decreased in Ang II-treated hearts. Relaxation is an energy-consuming process since ATP hydrolysis is required for myosin detachment from actin, Ca\textsuperscript{2+} dissociation from Tn-C, and active sequestration of Ca\textsuperscript{2+} by the sarcoplasmic reticulum. Loss of ATP production and a rise in the ADP/ATP ratio has been linked to diastolic dysfunction in hypertrophied hearts.\textsuperscript{16, 17} Our results support a key role of Ang II-mediated diastolic dysfunction mediated by metabolic perturbations coupled with increased interstitial myocardial fibrosis.\textsuperscript{18}

While Ang II-reduced carbohydrate oxidation is expected to lead to a compensatory rise in fatty acid oxidation based on the Randle principle, palmitate oxidation was actually slightly decreased or showed no change in response to Ang II and PE, respectively. The lack of a compensatory increase in palmitate oxidation may be due to Ang II-induced impairment of
mitochondria function due to NADPH oxidase mediated ROS production. Reductions in total acetyl CoA production and expression of complex I in response to Ang II are consistent with impaired mitochondrial function. Treatment with irbesartan significantly increased palmitate oxidation normalized for cardiac work and AT1R blockers are known to possess AT1R-independent effects including an increase in the expression of PPARs. Indeed, we showed that irbesartan increased complex I, PPARα and ERRα levels, leading to an increase in palmitate oxidation. Furthermore, under conditions where Ang II and irbesartan were co-administered, Ang II is more likely to bind and activate the AT2R, which may also contribute to the observed alterations in cardiac metabolism. Metabolic modulators aimed at shifting metabolism from fatty acid towards glucose oxidation, which have recently been shown for hypertrophic cardiomyopathy treatment, may serve as a novel therapy for HFNEF.

Although the ERRα/PPARα axis is known to up-regulate PDK4 expression, consistent with previous findings we showed Ang II induced down-regulation of PPARα and ERRα which would be expected to reduce PDK4 expression and increase glucose oxidation. In contrast, we show that the expression of PDK4 is increased with inhibitory phosphorylation of PDH, resulting in reduced glucose and lactate oxidation rates. Importantly, we showed a critical role of the cyclin/CDK-pRB-E2F1 axis in the Ang II-induced up-regulation of PDK4. E2F1 is known as a transcriptional factor and a critical regulator in the development of cardiac hypertrophy, while cyclin D1 assembles with CDK4. The complex phosphorylates and inactivates Rb, which represses nuclear E2F1. In addition, the nuclear translocation of the complex of CDK4 and cyclin D1
enhances the expression of phospho-cyclin D1 in cytosol.\textsuperscript{47, 48} In the setting of cardiac hypertrophy, cyclin D1 is up-regulated thus leading to activation of E2F1,\textsuperscript{49, 50} while in human HF increased expression of pRb, cyclin D1 and E2F1 is reversible in response to ventricular unloading.\textsuperscript{51} Ang II-induced hypertrophy results in activation of E2F1 in skeletal muscle, resulting in enhancement of protein synthesis and energy production\textsuperscript{52} while E2F1 regulates the expression of PDK4 and glucose oxidation.\textsuperscript{53} We demonstrate the up-regulation of p-Rb, enhanced expression of cytosolic phospho-cyclin D1 and accumulation of nuclear E2F1 in response to Ang II. Human studies suggest that in HF there is a decreased fatty acid β-oxidation and increased glucose uptake in the heart.\textsuperscript{31} However, alterations of glucose oxidation in human HF are not that well characterized, primarily because it is difficult to directly measure glucose oxidation rates in human hearts. Also, alterations in cardiac metabolism can vary depending on the severity of HF.\textsuperscript{54} We report the specific reduction in carbohydrate oxidation in Ang II and PE-induced preclinical models of HFNEF. Ang II-specific activation of PDK4 via E2F1 and AT1R blockade prevents these changes, which supports E2F1 playing a pivotal role in Ang II-induced alterations in cardiac metabolism.

In conclusion, Ang II and PE-mediated suppression of glucose oxidation correlated with the development of pathological hypertrophy and diastolic dysfunction. Ang II induces a reduction in glucose oxidation via the cyclin/CDK-pRB-E2F axis leading to increased PDK4 levels. Suppression of the cyclin/CDK-pRB-E2F axis and/or inhibition of PDK4 represent potential new therapeutic tools for treatment of HFNEF.
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Disclosures

JM is a fellow of the Mazankowski Alberta Heart Institute. GYO is an Alberta Innovates Health Solution (AIHS) Clinician Investigator and a Distinguished Clinician-Scientist of the Heart and Stroke Foundation of Canada (HSFC) and Canadian Institutes of Health Research (CIHR). GDL is an AIHS Scientist and ZK is an AIHS Scholar and HSFC New Investigator.

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Figure Legends

**Figure 1.** Angiotensin II (Ang II) induces concentric hypertrophy and diastolic dysfunction. Echocardiographic assessment showing M-mode (A) and short-axis view (B) illustrating concentric hypertrophy with normal systolic function as quantified by increased LV posterior wall thickness (LVPWT) (C) and normal LV ejection fraction (LVEF) (D). Transmitral mitral Doppler flow (E) and tissue Doppler imaging (F) showing diastolic dysfunction as illustrated by decreased E/A ratio (G) and increased E/E’ ratio (H) in Ang II-treated mice. Ang II type 1 receptor (AT1R) blockade with irbesartan prevents Ang II-induced concentric hypertrophy and diastolic dysfunction (A-H). E-wave, peak early transmitral inflow mitral E velocity; A-wave, transmitral inflow velocity due to atrial contraction and E’, early diastolic tissue Doppler velocity. Values are mean±SEM of n=9-12 in each group; *p<0.05 compared with all groups.

**Figure 2.** Angiotensin II (Ang II) mediates metabolic perturbations in the heart characterized by reduced carbohydrate oxidation. Ang II reduced cardiac work (A) with reduction in glucose oxidation (B) and lactate oxidation (C) while palmitate oxidation (D) was not significantly decreased. The contributions of acetyl CoA production from glucose oxidation, lactate oxidation, palmitate oxidation are shown for all groups (E). Ang II significantly reduced glucose normalized by cardiac work (F), but neither palmitate oxidation normalized by cardiac work (G) nor lactate oxidation normalized by cardiac work (H). Ang II type 1 receptor (AT1R) blockade with irbesartan prevents Ang II-induced metabolic perturbations in the heart. Glucose oxidation
(B) and lactate oxidation (C) are significantly increased in response to irbesartan. Irbesartan treatment also significantly increased palmitate oxidation (D) while restoring acetyl CoA production (E). While AT1R normalized glucose oxidation per cardiac work (F), both palmitate and lactate oxidation per cardiac work were significantly increased above baseline values (G and H). Values are mean±SEM of n=10-13 in each group; *p<0.05 compared with vehicle-treated group; †p<0.05 compared with Ang II-treated group.

**Figure 3.** Mechanism of angiotensin II (Ang II)-mediated reduction in carbohydrate oxidation. Up-regulation of pyruvate dehydrogenase kinase 4 (PDK4) levels (A) resulting in reduced active pyruvate dehydrogenase (PDH) activity (B) with unaltered total PDH activity (C) and the up-regulation of phospho-PDH levels (D). The expression of PDK4 was reduced (E) resulting in elevation in active PDH activity (F) with no change in total PDH activity (G) by treatment with irbesartan. These changes correlated with reduced phospho-PDH levels in response to irbesartan (H). A.U. indicates arbitrary units. Values are the mean±SEM of n=6-7 in each group; *p<0.05 compared with vehicle-treated group; †p<0.05 compared with Ang II+Placebo group.

**Figure 4.** Cardiac expression of the cell cycle regulators, E2F1, p-Rb, CDK4 and phospho-cyclin D1 in response to Angiotensin II (Ang II). Increased nuclear expression of E2F1 (A), cytosolic expression of p-Rb (B), nuclear expression of CDK4 in the nucleus (C) with increased phosphorylation of cyclin D1 in the cytosol in response to treatment with Ang II. The
expressions of E2F1 in the nucleus (E), p-Rb in the cytosol (F), CDK4 in the nucleus (G) and phospho-cyclin D1 (H) in the cytosol are reversed in response to treatment with irbesartan. A.U. indicates arbitrary units. Values are the mean±SEM of n=5 in each group; *p<0.05 compared with vehicle-treated group; †p<0.05 compared with Ang II+Placebo group.

Figure 5. Phenylephrine (PE)-induced concentric hypertrophy with diastolic dysfunction is associated with selective reduction in glucose oxidation. Echocardiographic assessment showing M-mode (A) illustrating concentric hypertrophy with normal systolic function as quantified by increased LV posterior wall thickness (LVPWT) and normal LV ejection fraction (LVEF) and velocity of circumferential shortening corrected for heart rate (VCFc) (B). Transmitral mitral Doppler flow (C) and tissue Doppler imaging (D) showing diastolic dysfunction as illustrated by reduced E/A ratio (E) and decreased E′/A′ ratio (F) in response to treatment with PE. Metabolic profiling showing a selective reduction in glucose oxidation (G) with no change in palmitate oxidation (H) driven by increased pyruvate dehydrogenase kinase 4 (PDK4) levels (I), increased phospho-PDH levels (J) and reduced active pyruvate dehydrogenase (PDH) activity (K) in hearts from PE-treated mice. E-wave, peak early transmitral inflow mitral E velocity; A-wave, transmitral inflow velocity due to atrial contraction; E′, early diastolic tissue Doppler velocity. Values are mean±SEM of n=9 in each group; *p<0.05 compared with vehicle-treated group.
Figure 2
Figure 3
Figure 4
Figure 5

A

WT + Placebo

WT + PE

B

Palmitate Oxidation (nmol g dry wt$^{-1}$ min$^{-1}$)

Glucose Oxidation (nmol g dry wt$^{-1}$ min$^{-1}$)

C

WT + Placebo

WT + PE

D

WT + Placebo

WT + PE

E

F

G

H

I

J

K

PDK4

$\alpha$-tubulin

Vehicle

PE

Vehicle

PE

Vehicle

PE

Vehicle

PE

Active PDH activity (nmol g heart$^{-1}$ min$^{-1}$)
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SUPPLEMENTAL MATERIAL

Agonist-induced hypertrophy and diastolic dysfunction is associated with selective reduction in glucose oxidation: a metabolic contribution to heart failure with normal ejection fraction

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Supplemental Methods

In vivo Cardiac Function

Transthoracic echocardiography was performed and analyzed in blinded manner as described previously with a Vevo 770 high-resolution echocardiography imaging system equipped with a 30-MHz transducer (RMV-707B; VisualSonics, Toronto, Canada). Mice were anesthetized by isoflurane.

Heart Perusions

After 14 days treatment with Vehicle or, Ang II with or without irbesartan, mice were euthanized by an intraperitoneal injection of sodium pentobarbital. Subsequently, the hearts were isolated and inserted cannula via the aorta and the left atrium, as described previously. After equilibration in the Langendorff mode, hearts were switched to the working mode. Isolated working hearts from mice were perfused with modified Krebs-Henseleit buffer containing 5mM glucose, 1.2mM palmitate, 1mM lactate and 100 µU/mL insulin. Perfusate was labeled with either [U-14C]lactate and [5-3H]glucose for measurement of lactate oxidation and glycolysis, or in a parallel series with [9,10-3H]palmitate and [U-14C]glucose for palmitate oxidation and glucose oxidation measurements. The palmitate was pre-bound to 3% fatty acid free bovine serum albumin. Hearts were spontaneously perfused at a left atrial preload of 11.5
mmHg and an aortic afterload of 50 mmHg. The rates of glucose oxidation and lactate oxidation were measured by quantitative collection of $^{14}$CO$_2$, and the rates of palmitate oxidation and glycolysis were measured by quantitative collection of $^3$H$_2$O. At the end of the 40min aerobic perfusion, hearts were frozen by liquid N$_2$ and stored at -80°C until used for subsequent biochemical analyses.

**Evaluation of Cardiac Hypertrophy**

After heart perfusions, ventricular muscles were cut to separate from atriums. Atriums were dried in the oven overnight. Dried atriums were weighed (Dry Atria). Ventricular muscles were frozen by liquid nitrogen. Frozen ventricles were weighed (Whole Vent) and crushed with muller. About 10 mg of ventricular muscle powder was weighed (Wet Vent powder) and dried in the oven overnight. The dried powder was also weighed (Dry Vent powder). Dry Wt and %Dry Wt/Body Wt were calculated as below, respectively: Dry Wt (g)=$(\text{Dry atria})+(\text{Dry Vent powder})/(\text{Wet Vent powder})*(\text{Whole Vent})$, %Dry Wt/Body Wt=Dry Wt/Body Wt * 100.

**TaqMan Real-Time Polymerase Chain Reaction**

RNA expression levels were also measured to estimate cardiac hypertrophy by TaqMan real-time polymerase chain reaction, as previously described.$^4, 5$ Total RNA was extracted using TRIzol, and cDNA was synthesized from 1μg RNA. A standard curve was generated by using known concentrations of cDNA as a function of cycle threshold. Expression of genes was analyzed by TaqMan real-time PCR using ABI 7900 Sequence Detection System. 18S rRNA was used as an internal control.

**PDH Activity**

PDH activities were measured using a revised protocol based on the radiometric assay described by Constantin-Tepdosiu et al.$^6$ Briefly, for measurement of active PDC, frozen cardiac muscle tissue was homogenized in buffer containing 200mM sucrose, 50mM KCl, 5mM EGTA, 50mM Tris-HCl, 50mM NaF, 50mM sodium pyrophosphate (NaPPI), 5mM dicholoroacetate, and 0.1% Triton X-100 (pH7.8). The samples were then incubated in assay buffer containing 150mM Tris-HCl, 0.75mM EDTA, 0.75mM nicotinamide adenine dinucleotid, 1.5mM thiamine pyrophosphate, and 0.75mM CoA. The reaction was initiated by the addition of pyruvate, incubated at 37°C, and terminated by the addition of perchloric acid. Samples were neutralized by KHCO$_3$ and centrifuged, and [14C]aspartate was added into the
resulting supernatant for determination of acetyl-CoA content. Acetyl CoA in each samples was converted to [14C]citrate and separated from unreacted radioactivity using Dowex resin (50WX8, 100-200 mesh). The amount of acetyl CoA was determined by comparison of acetyl CoA standard curve.

**Western Blot Analysis**

Western blot analyses were determined as described previously.\(^5,7\) Frozen ventricular tissue (25-30mg) was homogenized to extract protein by using buffer containing 50mM Tris-HCl (pH8 at 4°C), 1mM EDTA, 10% glycerol (wt/vol), 0.02% Brij-35 (wt/vol), 1mM dithiothreitol, protease and phosphatase inhibitors (Sigma). After quantification by Bradford protein assay kit (Bio-Rad), protein samples were separated by 8%~10% SDS-polyacrylamide gel electrophoresis and transferred onto a 0.45µm nitrocellulose membrane (Bio-Rad). The membrane was blocked with 5% milk in Tris-Buffered Saline Tween-20 for 1h and then probed with either anti-PDK4 (Abgent), anti-phospho-PDH (CalBiochem), anti-E2F1 (Cell Signaling Inc), anti-p-Rb (Cell Signaling Inc), anti-CDK4 (Cell Signaling Inc), anti-phospho-cyclin D1 (Cell signaling Inc) or anti-total-cyclin D1 (Cell Signaling Inc). Membranes were washed with TBST and subsequently probed with goat anti-rabbit secondary antibody (Santa Cruz Biotechnology) or goat anti-mouse secondary antibody (Santa Cruz Biotechnology) when appropriate. Immunoblots were visualized with the enhanced chemiluminescence Western blot detection kit (Perkin Elmer) and quantified with Image J software (U.S. National Institutes of Health, Bethesda, MD).

**Extraction of Nuclear and Cytoplasmic Protein**

We used nuclear proteins for E2F1 and CDK4 and cytoplasm protein for p-Rb, phospho-cyclin D1 and total-cyclin D1. Thus, we extracted the protein of nuclear and cytoplasm according to the modified Dignam’s protocol.\(^8\) We homogenized the tissue in buffer containing 10mM HEPES pH7.9, 1.5mM MgCl2, 10mM KCl, 0.5mM DTT and 1:1000 protease inhibitor. After homogenation, we centrifuged at 500g, 10min at 4°C. The supernatant (cytoplasmic protein extract) was carefully removed. The nuclei pellet was added with the buffer containing 20mM HEPES, 25% glycerol, 0.42M NaCl, 1.5mM MgCl2, 0.2mM EDTA, 0.5mM DTT, 0.5mM PMSF and 1:1000 protease inhibitor. Nuclear lysate was centrifuged at 14,000, 5min at 4°C. The supernatant (nuclear protein extract) was removed, followed by Western blot analysis as stated above.
**Supplemental Table 1. Echocardiographic assessment of cardiac function in WT mice in response to Ang II infusion (1.5 mg·kg⁻¹·d⁻¹) for 2 weeks and the effect of AT1R blockade**

<table>
<thead>
<tr>
<th></th>
<th>WT+Vehicle+ Placebo</th>
<th>WT+Ang II+ Placebo</th>
<th>WT+Ang II+ Irbesartan</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>483±12</td>
<td>492±17</td>
<td>478±15</td>
</tr>
<tr>
<td>E-wave (mm/s)</td>
<td>749±18</td>
<td>718±23</td>
<td>741±23</td>
</tr>
<tr>
<td>A-wave (mm/s)</td>
<td>431±15</td>
<td>543±16*</td>
<td>445±13</td>
</tr>
<tr>
<td>E/A Ratio</td>
<td>1.74±0.11</td>
<td>1.32±0.12*</td>
<td>1.67±0.12</td>
</tr>
<tr>
<td>IVRT (ms)</td>
<td>13.7±0.6</td>
<td>14.8±1.1</td>
<td>14.3±0.9</td>
</tr>
<tr>
<td>DT (ms)</td>
<td>28.3±1.4</td>
<td>25±1.7</td>
<td>27.6±1.6</td>
</tr>
<tr>
<td>EWDR (mm/s²)</td>
<td>26.5±2.1</td>
<td>28.7±3.2</td>
<td>26.8±2.8</td>
</tr>
<tr>
<td>E' (mm/s)</td>
<td>24.1±2.1</td>
<td>15.9±2.2*</td>
<td>25.2±2.6</td>
</tr>
<tr>
<td>E/E' Ratio</td>
<td>31.1±3.3</td>
<td>45.2±3.2*</td>
<td>29.4±2.9</td>
</tr>
<tr>
<td>A' (mm/s)</td>
<td>16.4±1.1</td>
<td>18.4±1.9</td>
<td>17.3±1.6</td>
</tr>
<tr>
<td>E'/A' Ratio</td>
<td>1.47±0.07</td>
<td>0.86±0.08*</td>
<td>1.46±0.06</td>
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<tr>
<td>LVEDD (mm)</td>
<td>3.76±0.08</td>
<td>3.43±0.11</td>
<td>3.72±0.12</td>
</tr>
<tr>
<td>LVESD (mm)</td>
<td>2.49±0.06</td>
<td>2.29±0.08</td>
<td>2.47±0.09</td>
</tr>
<tr>
<td>LVFS (%)</td>
<td>33.8±1.9</td>
<td>33.2±2.9</td>
<td>33.6±2.7</td>
</tr>
<tr>
<td>LVEF (%)</td>
<td>62.3±3</td>
<td>63.9±3.4</td>
<td>60.2±3.1</td>
</tr>
<tr>
<td>VCFc (circ/s)</td>
<td>6.45±0.17</td>
<td>6.61±0.23</td>
<td>6.56±0.21</td>
</tr>
<tr>
<td>LVPWT (mm)</td>
<td>0.68±0.05</td>
<td>0.95±0.08*</td>
<td>0.7±0.07</td>
</tr>
</tbody>
</table>

HR, heart rate; E-wave, peak early transmitral inflow mitral E velocity; A-wave, transmitral inflow velocity due to atrial contraction; IVRT, isovolumetric relaxation time; DT, deceleration time; EWDR, E-wave deceleration rate (E-wave/DT); E’, early diastolic tissue Doppler velocity; LVEDD, left ventricular (LV) end diastolic diameter; LVESD, LV end systolic diameter; LVFS, LV fractional shortening; LVEF, LV ejection fraction; VCFc, Velocity of circumferential shortening corrected for heart rate; LVPWT, LV posterior wall thickness. Results are presented as mean±S.E.M. *p<0.05 compared with all other groups.
Supplemental Table 2. Invasive hemodynamic measurement of cardiac function in WT mice in response to Ang II infusion (1.5 mg.kg⁻¹.d⁻¹) for 2 weeks and the effect of AT1R blockade

<table>
<thead>
<tr>
<th></th>
<th>WT+Vehicle+ Placebo</th>
<th>WT+Ang II+ Placebo</th>
<th>WT+Ang II+ Irbesartan</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>513±15</td>
<td>504±21</td>
<td>521±17</td>
</tr>
<tr>
<td>SBP (mmHg)</td>
<td>108±5.2</td>
<td>161.4±8.1*</td>
<td>121±4.8</td>
</tr>
<tr>
<td>DBP (mmHg)</td>
<td>69.3±3.1</td>
<td>114±5.7*</td>
<td>73.6±3.9</td>
</tr>
<tr>
<td>MABP (mmHg)</td>
<td>82.2±3.6</td>
<td>129.8±4.2*</td>
<td>89.4±3.5</td>
</tr>
<tr>
<td>+dP/dt_max (mmHg/s)</td>
<td>11031±369</td>
<td>11120±420</td>
<td>10992±386</td>
</tr>
<tr>
<td>-dP/dt_max (mmHg/s)</td>
<td>10004±322</td>
<td>7834±456*</td>
<td>9985±402</td>
</tr>
<tr>
<td>LVEDP (mmHg)</td>
<td>5.8±1.3</td>
<td>9.74±1.4*</td>
<td>6.15±2.3</td>
</tr>
</tbody>
</table>

HR, heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MABP, mean arterial blood pressure; +dP/dt_max=maximum negative and positive rate of change in LV pressure. Values are mean±SEM; *p<0.05 compared with all other groups.
### Supplemental Table 3. Mechanical function in the *ex vivo* perfused working heart model in response to Ang II

<table>
<thead>
<tr>
<th></th>
<th>WT+Vehicle+ Placebo</th>
<th>WT+Ang II+ Placebo</th>
<th>WT+Ang II+ Irbesartan</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>10</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Heart Rate (beats • min⁻¹)</td>
<td>284 ± 9</td>
<td>279 ± 10</td>
<td>283 ± 10</td>
</tr>
<tr>
<td>Peak systolic pressure(mmHg)</td>
<td>64 ± 1.3</td>
<td>66 ± 1.1</td>
<td>64 ± 1.8</td>
</tr>
<tr>
<td>Developed Pressure (mmHg)</td>
<td>29 ± 1.1</td>
<td>28 ± 1.2</td>
<td>31 ± 1.8</td>
</tr>
<tr>
<td>HR x PSP (bpm • mmHg • 10⁻³)</td>
<td>18 ± 0.6</td>
<td>18 ± 0.6</td>
<td>18 ± 0.9</td>
</tr>
<tr>
<td>HR x DP (bpm • mmHg • 10⁻³)</td>
<td>8 ± 0.3</td>
<td>7 ± 0.2</td>
<td>8 ± 0.4</td>
</tr>
<tr>
<td>Aortic Output (ml/min)</td>
<td>7.9 ± 0.44</td>
<td>7.1 ± 0.34</td>
<td>7.1 ± 0.75</td>
</tr>
<tr>
<td>Coronary Flow (ml/min)</td>
<td>3.3 ± 0.40</td>
<td>2.5 ± 0.29</td>
<td>3.5 ± 0.48</td>
</tr>
<tr>
<td>Cardiac Work/TCA acetyl CoA (joules/µmol)</td>
<td>0.30 ± 0.02</td>
<td>0.32 ± 0.02</td>
<td>0.24 ± 0.02*</td>
</tr>
</tbody>
</table>

HR, heart rate; PSP, peak systolic pressure; DP, developed pressure. Results are presented as mean±S.E.M; *p<0.05 compared with all other groups.
### Supplemental Table 4. Contribution of ATP production from glucose oxidation, lactate oxidation, palmitate oxidation and glycolysis

<table>
<thead>
<tr>
<th></th>
<th>WT+Vehicle+ Placebo</th>
<th>WT+Ang II+ Placebo</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Glucose oxidation (µmol/g dry wt/min)</td>
<td>24.4±1.5</td>
<td>15.4±1.1*</td>
</tr>
<tr>
<td>Lactate oxidation (µmol/g dry wt/min)</td>
<td>22.0±2.0</td>
<td>15.6±3.3</td>
</tr>
<tr>
<td>Palmitate oxidation (µmol/g dry wt/min)</td>
<td>54.3±10.1</td>
<td>47.2±3.0</td>
</tr>
<tr>
<td>Glycolysis (µmol/g dry wt/min)</td>
<td>33.0±6.4</td>
<td>26.1±5.5</td>
</tr>
</tbody>
</table>

Values are mean±SEM; *p<0.05 compared with WT+Vehicle+Placebo group.
Supplemental Figure Legends

Supplemental Figure 1. Angiotensin II (Ang II) induces cardiac hypertrophy. Left ventricular Dry Wt (A) and %Dry Wt/Body Wt (B) were significantly increased in Ang II-treated mice. Real-time polymerase chain reaction analysis revealed that Ang II increased the mRNA expression of pathological hypertrophic markers; atrial natriuretic peptide (ANP; C), brain natriuretic peptide (BNP; D), β-myosin heavy chain (β-MHC; E) and α-skeletal actin (α-SA; F). Picosirius red staining (G) showed increased cardiomyocyte cross-sectional area (MCA) (and interstitial fibrosis) in Ang II-treated hearts which was quantified and shown (H). R.E. indicates relative expression. Values are the mean±SEM of n=6-8 in each group; *p<0.05 compared with vehicle-treated group.

Supplemental Figure 2. Treatment with AT1R blocker, irbesartan, prevented Ang II-induced cardiac hypertrophy. Left ventricular Dry Wt (A) and %Dry Wt/Body Wt (B) were significantly decreased in the irbesartan group. Real-time polymerase chain reaction analysis revealed that irbesartan prevented Ang II-induced increase in the mRNA expression of pathological hypertrophic markers; ANP (C), BNP (D), β-MHC (E) and α-SA (F). R.E. indicates relative expression. Values are the mean±SEM of n=6-8 in each group; *p<0.05 compared with Ang II+Placebo group.

Supplemental Figure 3. Lack of a significant change between Ang II-treated and vehicle groups, in the expression of PDK2 (A) and β-hydroxyacyl CoA dehydrogenase activity (B) while Ang II reduces the expression of PPARα (C) and ERRα (D), which are well-known transcriptional factors of PDK4. The expression of complex I (E) was also reduced by Ang II, but citrate synthase activity (F) was unchanged in response to Ang II. Values are the mean±SEM of n=5 in each group; *p<0.05 compared with vehicle-treated group.

Supplemental Figure 4. Ang II-induced alterations in complex I (A), PPARα (B) and ERRα (C) were reversed by AT1R blockade leading to significant increases compared to placebo-treated group. A.U. indicates arbitrary units. Values are the mean±SEM of n=5 in each group; *p<0.05 compared with Ang II+Placebo group.
Supplemental Figure 5. Phenylephrine (PE) (40 mg.kg\(^{-1}.d^{-1}\) for 2 weeks) treatment increased the systolic blood pressure as measured using the tail cuff methodology in conscious mice (TC-SBP) (A) leading to increased left ventricular %Dry Wt/Body Wt (B). Values are the mean±SEM of n=8 in each group; *p<0.05 compared with vehicle-treated group.
Supplemental Figure 1
Supplemental Figure 2
Supplemental Figure 5
Supplemental References


