Cardiac $\beta$-adrenoceptor expression is markedly depressed in Ossabaw swine model of cardiometabolic risk

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Abstract: Ossabaw swine have a “thrifty genotype” and consumption of excess calories induces many classical components of the metabolic syndrome, including obesity, insulin resistance, impaired glucose tolerance, dyslipidemia, hyperleptinemia, and hypertension. Earlier studies indicate that the metabolic syndrome is associated with diminished cardiac function; however, to what degree this impairment is associated with alterations in myocardial $\beta_1$- and $\beta_2$-adrenoceptor (AR) expression has not been fully elucidated. Accordingly, the present study was designed to investigate the effects of the metabolic syndrome on cardiac $\beta_1$- and $\beta_2$-AR expression. Studies were conducted on left ventricular tissue samples obtained from control lean and chronically (50 weeks) high-fat-fed obese animals. Chronic feeding significantly increased fasting plasma insulin, total cholesterol, triglycerides, blood glucose, systolic and diastolic blood pressure, and heart rate. Real-time polymerase chain reaction revealed no significant alterations in cardiac $\beta_1$- and $\beta_2$-AR mRNA expression. In contrast, Western blot analysis revealed a significant decrease in ventricular $\beta_1$- and $\beta_2$-AR protein expression. This is the first report in a novel large animal model that induction of metabolic syndrome is accompanied by a significant reduction in cardiac $\beta_1$- and $\beta_2$-AR protein expression that could contribute to impaired cardiac function.

Keywords: hypertension, metabolic syndrome, $\beta$-AR, impaired cardiac function

Introduction
With the increasing burden of childhood obesity, the prevalence of metabolic syndrome in children still varies widely.1 However, using Adult Treatment Panel (ATP) III and World Health Organization criteria, a school-based study on metabolic syndrome has reported prevalence at 4.2% and 8.4%, respectively.1 Importantly, pediatric metabolic syndrome needs to be tracked very carefully from childhood to adulthood to prevent cardiometabolic risk.2 Metabolic syndrome is known to be associated with higher cardiovascular mortality and morbidity, which is referred to as “cardiometabolic risk” in the clinics.3 Despite genetic and environmental factors, the key elements of metabolic syndrome are obesity, impaired glucose tolerance, insulin resistance, increased low-density lipoprotein:high-density lipoprotein ratio, increased fasting and postprandial triglyceride levels, and hypertension.4 Specifically, centrally distributed adiposity in obesity strongly correlates with adult cardiometabolic risk.3

This multifaceted syndrome can result in a variety of cardiac and hemodynamic alterations that ultimately result in development of congestive heart failure.2,5 The mechanisms responsible for these disturbances are mainly multifactorial but could be related to a hyperdynamic circulatory state, which is characterized by increased...
blood pressure, total blood volume, cardiac output, and tissue metabolic demand. Basal catecholamine level generally increases, a finding supported by many studies. Increased sympathetic system activity could stimulate G-protein-coupled β-adrenoceptors (ARs), elevating intracellular cyclic adenosine monophosphate (cAMP), thereby activating protein kinase A (PKA) or calcium calmoduline kinase II (CaMKII). The duration of the disease is the key factor that attenuates β-AR-mediated cardiac responses and underlying mechanisms.

Determining the effects of metabolic syndrome on cardiac β-AR expression seems to be one of the novel therapeutic strategies against obesity-induced cardiometabolic risk. The author of this study determined hemodynamic parameters such as systolic, diastolic, and mean arterial blood pressures as well as heart rate. Real-time polymerase chain reaction (PCR) and Western blot analysis were used to assess mRNA and protein expressions in the left ventricles obtained from control and chronically (50 weeks) high-fat-fed animals. For that purpose, I selected obese Ossabaw swine, which are one of the novel large animals and the most similar model to human metabolic syndrome.

**Methods**

**High-fat diet**
This investigation was approved by the Indiana University School of Medicine Institutional Animal Care and Use Committee and was conducted in accordance with the Guide for the Care and Use of Laboratory Animals. Ossabaw pigs were fed either a normal diet (Teklad, −13% calories from fat; n = 7) or a high-fat diet (−60% of calories from fat; n = 9). The high-fat diet was administered in the morning and afternoon for 50 weeks. The pigs were maintained on this diet throughout the experimental protocol.

**Analytical procedures**
Plasma supernatant was collected and stored at −80°C.

**Isolation and quantitation of total RNA**
Left ventricles obtained from control and high-fat-fed Ossabaw swine. They were placed in liquid N2 and stored at −80°C. Total RNA was extracted according to manufacturer’s instructions (SV Total RNA Isolation System, Promega Corp, Fitchburg, WI). At the end of the isolation, RNA samples were dissolved in nuclease-free water (pH 7.5). The total RNA quantity and quality were determined using the Experion™ Semi-automated Electrophoresis System (Bio-Rad Laboratories, Inc, Hercules, CA). In the Experion priming station, the microfluidic-based LabChip sample wells (RNA StdSens Chips, Experion, Bio-Rad) were filled with a polymer-sieving matrix containing a fluorescent dye and 1 µL of denatured total RNA. The concentration of total RNA was determined by using the ratio of the sample RNA area to the Experion RNA ladder area. RNA samples with distinct 18S and 28S ribosomal RNA fragments in the electropherogram were used to assess RNA quality.

**Preparation of first-strand cDNA via reverse transcriptase reactions**
RNA samples were used as templates for synthesis of first-strand cDNAs as described previously. Briefly, 1 µL of oligo(dT)15 primer (Promega) was added to equivalent amounts of total RNA obtained from left ventricles isolated from control (n = 5) and chronically high-fat-fed (n = 5) pigs. The mixtures were then placed into a thermocycler (My Cycler™, Bio-Rad) and held at 70°C for 5 minutes. The samples were then transferred into an ice bath for 5 minutes to permit selective binding of the oligo(dT)15 to the poly(A) tail of the mRNA. First-strand cDNA was then synthesized with an ImProm-II Reverse Transcriptase kit (Promega).

**Amplification of cDNA**
Real-time PCR reactions were performed for β-ARs, β-ARs, and β-actin in triplicate with a custom-designed SYBR® Green mix (2.4 µL of 25 mM MgCl2, 5 µL of 1:10,000 dilution SYBR Green I, Molecular Probes, Inc, Eugene, OR) and 5 µL of 1 nM fluorescein calibration dye (1 mM/L in dimethyl sulfoxide, Bio-Rad) in 50 µL of total reaction using Taq DNA polymerase (Promega) in 50 µL of total reaction using Taq DNA polymerase (Promega). Primers were designed using the Genomatix Software Suite program (München, Germany) based on sequences published in the National Center for Biotechnology Information GenBank database. Gene-specific primers were used: for β-ARs, sense 5′-GACCGAAAGCAGGTGAATC-3′ and antisense 5′-CTCCCATCCCTTCCCTAGTC-3′ (242 bp product; accession number AF042454); for β-ARs, sense 5′-GCCATCGACTGCTATCACAA-3′ and antisense 5′-GGTTTGGGGAGTGAACCC-3′ (193 bp product; accession number U53185); for β-actin, primers were designed based on published sequences in the GenBank database (sense 5′-ACGTGGACATCAGGAGGAC-3′ and antisense 5′-ACATCTCCTGGAAGGTGGAC-3′; accession number U07786).

Amplification was carried out with iCycler iQ multicolor real-time PCR detection system (Bio-Rad) as follows:
45-second denaturation (94°C) followed by 45-second annealing and 1-minute extension (72°C), repeated for a total of 40 cycles. β-actin was amplified in each set of PCR reactions and served as an internal reference during quantitation to correct for operator and/or experimental variations. The data were analyzed in triplicate using the 2−ΔΔCt equation.8,17,19

$$\Delta\Delta C_t = (C_{\beta\text{-ARs}} - C_{\beta\text{-actin}})_{\text{high-fat diet}} - (C_{\beta\text{-ARs}} - C_{\beta\text{-actin}})_{\text{control}}$$ (1)

The mean threshold cycle (Ct) values for both the target (β1- and β2-ARs) and internal control (β-actin) genes were determined in each sample.

Western blot analysis of β1- and β2-AR proteins

Left ventricles from control (n = 5) and high-fat-fed (n = 5) Ossabaw swine were isolated and placed in liquid nitrogen and stored at −80°C. Ventricles were homogenized in 150 µL of buffer (50 mM Tris-HCl [pH 7.4], 150 mM NaCl, 1% Triton X-100 [Sigma-Aldrich, Inc, St Louis, MI], 0.1% SDS [sodium dodecyl sulphate], 1 mM EDTA [ethylenediamine tetraacetic acid], 10 µg/mL aprotinin, 10 µg/mL leupeptin, 10 µg/mL pepstatin, 5:1000 phenylmethylsulfonyl fluoride [200 nM], 5:1000 Na3VO4 [200 nM], and 5:1000 NaF [200 nM]). The homogenates were centrifuged at 45,000 rpm for 30 minutes at 4°C. The supernatants were collected at 45,000 rpm for 30 minutes at 4°C. The supernatants were collected and used for analysis. Protein quantity and quality were determined using the Experion Semi-automated Electrophoresis System. Basically, 4 µL of denatured protein for each sample was loaded into a Pro 260 chip (Experion, Bio-Rad). Equivalent amounts of protein were separated by gel electrophoresis (10% Tris-HCl Criterion Precast Gel, Bio-Rad). Proteins were transferred onto nitrocellulose membrane (0.2 µm, Schleicher and Schuell, London, England, UK) by semidry electroblotting (Trans Blot SD, Bio-Rad) at 15 V for 1 hour. The nitrocellulose membrane was soaked in 10 mM Tris-HCl containing 5% nonfat dry milk (Bio-Rad) and 0.7% polyoxyethylene-sorbitan monolaurate (Tween® 20, Promega), pH = 7.2, overnight at 4°C to block nonspecific sites. The membranes were then incubated with the β1- and β2-AR purified polyclonal antibodies (1:300 dilution in Tris-buffered saline [TBS] with 5% nonfat dry milk and 0.1% Tween 20; Santa Cruz Biotechnology, Santa Cruz, CA) for 2 hours at room temperature. β-actin receptor antiserum was used for internal control (1:3000 dilution in TBS with 5% nonfat dry milk and 0.1% Tween 20; Santa Cruz Biotechnology). Blots were washed and incubated with donkey anti-goat IgG-HRP secondary antibody (1:3000 dilution; Santa Cruz Biotechnology) for 1 hour at room temperature. Immunoactivity was visualized with an enhanced chemiluminescence Western blotting detection kit (Amersham ECL™ GST Western Blotting Detection Kit, GE Healthcare, Little Chalfont, UK). Quantitative assessment of band densities was performed by scanning densitometry.

Statistical analyses

Data are expressed as mean ± standard error of the mean. Statistical testing was directed to detect overall treatment effects. An unpaired t-test was used to compare differences in bodyweight, plasma sample and hemodynamic data, and specific β1- and β2-AR gene and protein expression between the control and high-fat-fed animals.

Results

Phenotype of Ossabaw swine

Chronic high-fat feeding caused many common features of the metabolic syndrome in Ossabaw swine: animals were obese, hyperinsulinemic, dyslipidemic, hypercholesterolemic, and hypertensive (Figure 1 and Table 1). In contrast, control (normal-fed) animals were lean, normotensive, normoglycemic, and had normal lipid profiles.

Hemodynamic parameters

A high-fat diet of 50 weeks induced many common features of the prediabetic metabolic syndrome. Systolic, diastolic, and mean arterial blood pressures and heart rate were significantly elevated in high-fat-fed Ossabaw swine, compared with their lean controls (Figure 1).

Figure 1 Systolic BP, diastolic BP, and heart rate from lean and chronic high-fat-diet Ossabaw swine. Systolic and diastolic BPs and heart rate were significantly elevated in the metabolic syndrome group.

Note: *P < 0.05 versus control.

Abbreviations: BP, blood pressure; HR, heart rate.
**Table 1** Chronic high-fat feeding significantly increased fasting blood glucose, fasting insulin level, total cholesterol, and triglyceride levels

|                          | Control group (n = 7) | High-fat-diet group (n = 9) |
|--------------------------|-----------------------|----------------------------|
| Fasting blood glucose (mg/dL) | 79 ± 3               | 106 ± 9*                   |
| Fasting insulin level (µU/mL) | 4.8 ± 1.6            | 12.1 ± 4.6*                |
| Total cholesterol level (mg/dL) | 57.0 ± 5.5          | 165.6 ± 8.3*               |
| Total triglyceride level (mg/dL) | 24.7 ± 3.2         | 49.6 ± 2.9*                |

**Note:** *P < 0.05 versus control.

mRNA and protein expression of cardiac β₁- and β₂-ARs in control and chronically high-fat-fed Ossabaw swine

The quality of total RNA was determined by using distinct 18S and 28S ribosomal RNA fragments in the electropherogram. All samples used for analysis were of the same quality and quantity demonstrated in microfluidic-based LabChip sample wells. However, real-time PCR revealed no significant alterations in ventricular β₁- and β₂-AR mRNA expression in high-fat-fed Ossabaw swine compared with their controls (Figure 2). Pro260 chip–automated gel electrophoresis was used for determining protein quality and quantity (Figure 3). Western blot analysis demonstrated a significant decrease in ventricular β₁- and β₂-AR protein expression (19.86% and 22.6%, respectively) (Figure 4).

**Discussion**

The purpose of the present investigation was to examine the hypothesis that metabolic syndrome could alter expression of cardiac β₁₂-AR subtypes. Syndrome X, the deadly quartet, insulin resistance syndrome, and metabolic syndrome have been described previously and have many features of obesity and insulin deficiency in humans. We selected high-fat-fed Ossabaw swine as a cardiometabolic risk model because it is a very well established research model on the cardiovascular system. Ossabaw swine have applicability to human cardiometabolic syndrome and have a “thrifty genotype.” If they are fed with a high-fat diet for a long time, they develop metabolic syndrome.

Chronic high-fat feeding caused many common features of the metabolic syndrome in Ossabaw swine, ie, obesity, hyperinsulinemia, dyslipidemia, hypercholesterolemia, and hypertension, compared with the lean control group (Table 1 and Figure 1). We found that their systolic, diastolic, and mean arterial blood pressures and heart rate were significantly elevated compared with their lean controls (Figure 1). This hemodynamic picture indicates that they have a hyperdynamic circulatory state, which demonstrates increased sympathetic system activity. These findings were very consistent with our previous studies, where acute high-fat feeding triggered positive-feedback mechanisms to correct hemodynamic
imbalances. These cardiovascular risk clusters could directly attenuate main cardiovascular function.

Increased sympathetic system activity could cause downregulation of cardiac β-ARs and could change their secondary and tertiary structures. A persistent hypercatecholaminergic state, which is seen in high cardiometabolic risk subjects, triggers reversible or irreversible protein modifications in cell surface receptors. Both β₁ and β₂ subtypes have been shown to functionally coexist in the human heart. The hazardous effects of elevated catecholamine levels are found to be mediated primarily by β₁-ARs contrary to β₂-AR stimulation, which may be adaptive in some cases. β₁- and β₂-ARs each couple to Gₛ; however, a growing body of recent evidence suggests that β₂-ARs also couple to inhibitory protein Gₛ. In spite of these differences, the author and colleagues have previously demonstrated that both β₁- and β₂-AR expression and β₁- and β₂-AR-mediated inotropic and chronotropic responses were decreased in chronic diabetic hearts. There are a number of explanations for decreased β-AR expression in metabolic syndrome. Systemic hemodynamic alterations, key protein modifications, and intrinsic functional changes are major factors in attenuating β-AR-dependent cardiac inotropic and chronotropic responses.

This study found that chronic high-fat feeding resulted in decreased ventricular β₁- and β₂-AR protein expression, as expected. Real-time PCR revealed no significant alterations in ventricular β₁- and β₂-AR mRNA. These data directly demonstrate that downregulation of ventricular β₁- and β₂-ARs is possibly related to constant sympathetic system
stimulation. Increased sympathetic system activity stimulates β-ARs and elevates intracellular cAMP, thereby activating PKA and/or CaMKII. Recent evidence demonstrates that constant β-ARs stimulation switches the signaling pathway from PKA to CaMKII predominance in more chronic stages. Activation of the CaMKII pathway instead of PKA as well as PKA activity and underlying mechanisms were not determined; further experimentation is necessary.

Conclusion
This is the first report in a novel large animal model where induction of metabolic syndrome is accompanied by a significant reduction in cardiac β1- and β2-AR protein expression that could contribute to impaired cardiac function.

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Author’s contributions
U Deniz Dincer MD, PhD designed the experiment and analyzed the data discussed in this paper, and wrote the manuscript. This work was completed at the Indiana University School of Medicine, Department of Cellular and Integrative Physiology, IUPUI, Indianapolis, IN (Dr JD Tune’s laboratory).

Disclosure
The author reports no conflicts of interest in this work.

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