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Citation for published version (APA):

Document status and date:
Published: 01/10/2011

DOI:
10.1152/ajpendo.00106.2011

Document Version:
Publisher's PDF, also known as Version of record

Document license:
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Download date: 17 Sep. 2023
Absence of fatty acid transporter CD36 protects against Western-type diet-related cardiac dysfunction following pressure overload in mice

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Submitted 4 March 2011; accepted in final form 25 June 2011

Steinbusch LK, Luiken JJ, Vlashlom R, Chabowski A, Hoebers NT, Coumans WA, Vroegrijk JO, Voshol PJ, Ouwens DM, Glatz JF, Diamant M. Absence of fatty acid transporter CD36 protects against Western-type diet-related cardiac dysfunction following pressure overload in mice. Am J Physiol Endocrinol Metab 301: E618–E627, 2011. First published June 28, 2011; doi:10.1152/ajpendo.00106.2011.—Cardiac patients often are obese and have hypertension, but in most studies these conditions are investigated separately. Here, we aimed at 1) elucidating the interaction of metabolic and mechanophysical stress in the development of cardiac dysfunction in mice and 2) preventing this interaction by ablation of the fatty acid transporter CD36. Male wild-type (WT) C57Bl/6 mice and CD36+/− mice received chow or Western-type diet (WTD) for 10 wk and then underwent a sham surgery or transverse aortic constriction (TAC) under anesthesia. After a 6-wk continuation of the diet, cardiac function, morphology, lipid profiles, and molecular parameters were assessed. WTD administration affected body and organ weights of WT and CD36+/− mice, but it affected only plasma glucose and insulin concentrations in WT mice. Cardiac lipid concentrations increased in WT mice receiving WTD, decreased in CD36+/− on chow, and remained unchanged in CD36+/− receiving WTD. TAC induced cardiac hypertrophy in WT mice on chow but did not affect cardiac function and cardiac lipid concentrations. WTD or CD36 ablation worsened the outcome of TAC. Ablation of CD36 protected against the WTD-related aggravation of cardiac functional and structural changes induced by TAC. In conclusion, cardiac dysfunction and remodeling worsen when the heart is exposed to two stresses, metabolic and mechanophysical, at the same time. CD36 ablation prevents the metabolic stress resulting from a WTD. Thus, metabolic conditions are a critical factor for the compromised heart and provide new targets for metabolic manipulation in cardioprotection.

lipids; cardiac hypertrophy; metabolic flexibility; obesity

The healthy heart preferably utilizes long-chain fatty acids (60–70%) but also glucose (30–40%), lactate, and ketone bodies (29, 37). Under normal conditions, there is a distinctive and finely tuned utilization balance between these fuel substrates for ATP generation such that high fatty acid supply inhibits glucose metabolism (14, 16, 22). Under stressful conditions such as ischemia or hypertension, glucose is the preferred substrate because it requires less oxygen for its oxidation than an equimolar amount of carbons derived from fatty acids (16). Thus, the normal heart is able to switch between substrates according to the most favorable energetic yield needed for the prevailing cardiac condition (22).

Obesity, metabolic syndrome, and type 2 diabetes are associated with an increased risk of cardiovascular disease and heart failure (29). In obesity and its related conditions, plasma fatty acid and triglyceride (TG) concentrations are elevated, and plasma glucose levels gradually increase in the presence of insulin resistance (38). Collectively, these abnormalities impose metabolic stress on the heart (21, 27, 40, 45), which may ultimately lead to cardiac metabolic inflexibility, lipotoxicity (27), and subsequent development of metabolic cardiomyopathy in both rodents and humans (19, 29, 33, 34, 40, 44). Cardiac patients often are obese and have hypertension, but both conditions are studied mostly separately. In this study, we aimed at clarifying the interaction of metabolic and mechanophysical stress in the development of cardiac dysfunction.

CD36 is the predominant cardiac fatty acid transporter and is responsible for the majority of cardiac fatty acid uptake, as shown in studies with CD36+/− mice (18). In the normal heart, CD36 is distributed equally between the sarcolemmal and intracellular membrane storage compartments. However, in rat models for obesity and insulin resistance, we and others have found that the fatty acid transporter CD36 is permanently relocated to the sarcolemma, thereby increasing the contribution of fatty acids to (cardiac) muscle energy metabolism (1, 10, 32). This chronic increase in CD36-mediated fatty acid uptake caused 1) the gradual buildup of fatty acid metabolites, 2) reduced insulin-stimulated myocardial glucose uptake, measured by in vivo positron emission tomography (43) and cardiomyocyte glucose uptake (10, 32), and 3) decreased cardiac contractile function (32, 43). In aging studies in mice, there was an association between CD36-mediated fatty acid uptake and age-induced diabetes and cardiomyopathy (25). However, these studies could not make any strong conclusions on the possible causal relationship between CD36 presence at the sarcolemma and the development of diabetic cardiomyopathy.

Cardiac remodeling may occur as an adaptation to the metabolic stresses mentioned above but also in response to
mechanophysical and genetic stresses (41). Recent findings have indicated that the consequences of chronic metabolic stress and the development of metabolic inflexibility may become apparent only in the presence of additional cardiac stresses such as ischemia and hypertension (23, 26, 31). Accordingly, it was shown that short-term lowering of plasma fatty acid levels by acipimox had no effect on cardiac function in normal controls, whereas it did affect cardiac function in patients with heart failure (42). In summary, the effect of chronic metabolic stress on mechanophysical stress is not clear yet.

In this study, we aimed at further elucidating the interaction of metabolism and function in the compromised heart. First, we hypothesized that metabolic stress and mechanophysical stress interact in the development of cardiac dysfunction in mice. Second, we hypothesized that ablation of CD36 could prevent this interaction. Mechanophysical stress was induced by pressure overload after transverse aortic constriction (TAC), and metabolic stress resulted from exposure to a Western-type diet (WTD).

**EXPERIMENTAL PROCEDURES**

Twelve-week-old male wild-type (WT) and CD36<sup>−/−</sup> mice were fed ad libitum either standard rodent diet (chow, 1206; Harlan Teklad) or a WTD (D12079B; Open Source Research Diets). Ten weeks after initiation of the diet, mice either were sham operated (5–8 for each group) or underwent TAC (7–10 for each group) to induce pressure overload (Fig. 1A). Diet exposure was continued throughout the study. Six weeks after surgery, cardiac function was determined by echocardiography, and mice were euthanized by decapitation.

**Experimental animals.** CD36<sup>−/−</sup> mice were kindly provided by M. Febbraio (Cornell University, Ithaca, NY) and bred at Leiden University Medical Center (Leiden, The Netherlands). Mice were generated by targeted homologous recombination and crossed back eight times to the C57Bl/6 background (12). C57Bl/6 controls were purchased from Charles River Laboratories. All animal procedures were performed according to the Guide for the Care and Use of Laboratory Animals published by the European Commission Directive 86/609/EEC, and in addition they were approved by the Experimental Animal Committees of Maastricht University and Leiden University Medical Center, The Netherlands.

Fig. 1. Experimental setup and general parameters after 10 wk of diet exposure. A: experimental setup. B: Western blot image of CD36 protein presence in wild-type (WT) and CD36<sup>−/−</sup> mice on chow or Western-type diet (WTD). C: body weight during 10 wk of diet exposure. D: fasting blood glucose (FBG). E: cardiac function; fractional shortening was measured by thoracic echocardiography in anesthetized mice. F: plasma fatty acid and plasma insulin concentrations after diet exposure. Data are means ± SE from 20 mice on either diet for A–D and from 6 to 8 mice/group for E and F. Statistical analysis was done by 2-way ANOVA. *Vs. WT chow; ^vs. CD36<sup>−/−</sup>/chow; #vs. WT/WTD. TAC, transverse aortic constriction.
CD36 and Interacting Stresses in Cardiomyopathy

Diet composition. Chow consisted of 330 kcal/100 g divided over 16% proteins, 3.5% fat (mostly palmitic and linoleic acid), and 60.89% carbohydrates (mainly starch). WTD contained 469 kcal/100 g divided over 17% protein, 41% fat (27.21% palmitic, 26.81% oleic, 12.41% stearic, and 10.17% myristic acid), and 43% carbohydrates (primarily sucrose).

TAC. TAC was performed as described previously (20). Mice were anesthetized (induction: ip ketamine-xylazine, 100 and 5 mg/kg, respectively; maintenance isoflurane 1–2%), and 0.1 mg/kg Temgesic was injected subcutaneously for pain relief. The thorax was opened at the sternum, and TAC was induced by ligation of the aortic branch around a 27-gauge needle using a 6.0 silk suture. Sham-operated mice underwent a similar operation without the aorta being constricted.

Echocardiography. Transthoracic echocardiography was performed in anesthetized mice (3% isoflurane induction and 0.8–1% maintenance) using an Aloka Terson 3000cv. During B-mode and M-mode, recording heart rate was kept at 500 beats/min by adjustment of isoflurane. Left ventricle (LV) fractional shortening (FS) was calculated as described previously (13). Echocardiography was performed by two persons who were blinded for experimental groups. Interindividual differences in recordings were calculated, and values were adjusted accordingly.

Organ weight and blood glucose. Body weight and blood glucose levels were determined at 12 wk of age, after 10 wk of diet intervention and 6 wk after surgery. After 6 h of fasting, blood glucose was measured by glucose strips and a glucometer from Bayer Ascensia (LVEDD; Fig. 2). Cardiac function 6 wk after TAC.

Organ weight and blood glucose. Body weight and blood glucose levels were determined at 12 wk of age, after 10 wk of diet intervention and 6 wk after surgery. After 6 h of fasting, blood glucose was measured by glucose strips and a glucometer from Bayer Ascensia (LVEDD; Fig. 2). Cardiac function 6 wk after TAC.

Histology. Deparaffinized LV sections (4 µm) were stained with hematoxylin-eosin to determine cardiomyocyte cross-sectional area. Only regions that included circular-shaped cardiomyocytes with visible nuclei were analyzed. The mean cross-sectional area was determined from 60 to 100 cells for each mouse using QWin V3 software (Leica). Macrophages were visualized by a Mac3 staining (Pharmigen no. 553322) with alkaline phosphatase. The staining was scored on a five-point scale.

Heart TG, diglyceride, and ceramide concentrations. Heart lipids were determined in snap-frozen and freeze-dried tissue samples, as described previously (3). Intramyocardial lipids were extracted in methanol-chloroform, and an internal standard and water were added. One portion of the chloroform layer was used for TG and diglyceride (DG) separation, and another portion was used for ceramide determination. Afterward thin-layer chromatography was used to separate lipids, and samples were analyzed by gas-liquid chromatography.

Gene expression. Total RNA was isolated from heart tissue, as described previously (39), and converted into first-strand cDNA with the iScript cDNA synthesis kit (Bio-Rad) according to the manufacturer’s instructions. Changes in gene expression were determined by quantitative PCR, as described previously (39). To standardize for the amount of cDNA, hypoxanthine phosphoribosyl transferase (HPRT) was used as a reference gene. Primer sets (Supplemental Table S1; Supplemental Material for this article is available online at the AJP-Endocrinology and Metabolism web site) were developed with Primer Express version 1.5 (Applied Biosystems, Foster City, CA) using default settings. Quantitative PCR data was analyzed according to the relative standard curve method.

Protein detection. LV homogenates were used for protein detection by SDS-polyacrylamide gel electrophoresis, followed by Western blotting, as described previously (4). Antibodies were purchased at different companies or were kind gifts (Supplemental Table S2). Western blot images were analyzed with a Molecular Imager (Chemiluminescent XRS; Bio-Rad) and quantified with Quantity One (Bio-Rad).

Data presentation and statistics. Results are presented as means ± SE. Data were analyzed by two-way ANOVA with Bonferroni post hoc test and Kaplan-Meier survival test using GraphPad Prism 5.0. Two-sided values of P < 0.05 were considered significant.

RESULTS

Characteristics at baseline and after 10 wk of diet intervention. At 12 wk of age, WT and CD36+/− mice had similar body weights and cardiac function (Supplemental Table S3), and CD36−/− mice showed no cardiac CD36 protein presence (Fig. 1B). After 10 wk of diet intervention, mice exposed to WTD had gained significantly more body weight than those receiving chow, irrespective of the genotype (Fig. 1C). Six weeks after TAC surgery, mice receiving WTD continued to have higher body weights than mice receiving chow, regardless of the genotype (Supplemental Table S4). Remarkably, WTD-induced increases in liver mass contributed to a markedly larger extent to the increase in body weight when sham-operated CD36−/− mice were compared with WT mice (Supplemental Table S4). WTD-induced alterations in fat pad weights were similar for both genotypes (Supplemental Table S4). This relates to the notion that the genetic ablation of CD36 shifts the lipid load to tissues, such as the liver, that do not rely on CD36 for uptake of fatty acids (17).

After 10 wk of diet intervention, WT mice receiving WTD had higher fasting blood glucose levels than WT mice receiv-
Table 1. Body weight and parameters of cardiac remodeling when mice were 28 wk old (after 16 wk of diet intervention and 6 wk of TAC)

<table>
<thead>
<tr>
<th></th>
<th>Sham</th>
<th>CD36&lt;sup&gt;-/-&lt;/sup&gt;</th>
<th>TAC</th>
<th>CD36&lt;sup&gt;-/-&lt;/sup&gt;</th>
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<tr>
<td></td>
<td>WT</td>
<td>WTD</td>
<td>WT</td>
<td>WTD</td>
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<tr>
<td>Body weight</td>
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<td></td>
<td></td>
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<tr>
<td>Diastole</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior wall thickness</td>
<td>0.9 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td>0.8 ± 0.1</td>
<td>1.0 ± 0.1</td>
</tr>
<tr>
<td>Posterior wall thickness</td>
<td>0.9 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td>0.9 ± 0.0</td>
<td>1.0 ± 0.0</td>
</tr>
<tr>
<td>Total diameter</td>
<td>5.4 ± 0.1</td>
<td>5.6 ± 0.1</td>
<td>5.4 ± 0.1</td>
<td>5.7 ± 0.1</td>
</tr>
<tr>
<td>End-diastolic diameter</td>
<td>3.6 ± 0.2</td>
<td>3.5 ± 0.1</td>
<td>3.7 ± 0.1</td>
<td>3.7 ± 0.1</td>
</tr>
<tr>
<td>Systole</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior wall thickness</td>
<td>1.1 ± 0.1</td>
<td>1.3 ± 0.1</td>
<td>1.1 ± 0.1</td>
<td>1.2 ± 0.0</td>
</tr>
<tr>
<td>Posterior wall thickness</td>
<td>1.3 ± 0.1</td>
<td>1.3 ± 0.1</td>
<td>1.2 ± 0.0</td>
<td>1.3 ± 0.1</td>
</tr>
<tr>
<td>Total diameter</td>
<td>5.0 ± 0.1</td>
<td>5.3 ± 0.1</td>
<td>5.2 ± 0.1</td>
<td>5.3 ± 0.1</td>
</tr>
<tr>
<td>End-systolic diameter</td>
<td>2.7 ± 0.1</td>
<td>2.6 ± 0.1</td>
<td>2.7 ± 0.1</td>
<td>2.9 ± 0.1</td>
</tr>
</tbody>
</table>

Values are means ± SE. TAC, transverse aortic constriction; WT, wild type; WTD, Western-type diet. Each group consisted of 6–8 mice. *P < 0.05 vs. WT/chow; †P < 0.05 vs. sham; ‡P < 0.05 vs. chow/sham.

ing chow (Fig. 1D), whereas fasting blood glucose concentrations did not change upon WTD administration in CD36<sup>-/-</sup> mice. Plasma fatty acid concentrations were elevated in both WT WTD mice and CD36<sup>-/-</sup> chow mice (Fig. 1F). WTD administration in CD36<sup>-/-</sup> mice resulted in a decrease in plasma fatty acid levels, suggesting that hepatic storage of fatty acid was increased. Plasma insulin levels were elevated in WT mice upon WTD administration in CD36<sup>-/-</sup> mice (Fig. 1G), suggesting that CD36 ablation prevents the development of WTD-induced metabolic alterations. In agreement with this, WTD administration only altered genes important in fatty acid metabolism, e.g., long-chain acetyl-CoA synthetase, in hearts of WT mice but not in CD36<sup>-/-</sup> mice (Fig. 5). Interestingly, 10 wk of WTD administration did not affect FS in any experimental group (Fig. 1E). In conclusion, WT and CD36<sup>-/-</sup> mice have similar body weights and cardiac function at 12 wk of age. Ten weeks of metabolic stress affects body and organ weight, but not cardiac function, in both genotypes and affects only blood glucose and insulin levels in WT mice.

Parameters of cardiac function. Surgery survival was 100% for sham-operated groups for both the acute phase and...
the remainder of the study. For the TAC group the survival rate was 69% for the acute phase of the TAC surgery and 73% for the remainder of the study. TAC resulted in a significant decrease in FS of 26% in WT mice receiving a WTD as well as a significant decrease in FS of 35% in CD36<sup>−/−</sup> mice receiving chow (Fig. 2). These changes in FS were reflected mainly in increased left ventricular end systolic diameter (LVESD; Fig. 2B); there was a strong increase in both WT WTD mice and CD36<sup>−/−</sup> chow mice. Additionally, these changes in FS resulted from increased wall thicknesses and altered LV diameters in diastole (only for WT WTD; Fig. 2C and Table 1). However, cardiac function was preserved in CD36<sup>−/−</sup> on a WTD after TAC (Fig. 2), although their wall thickness was slightly increased (Table 1). No interaction of sham and WTD on cardiac function was found, regardless of the genetic background (Fig. 2), which is compatible with the lack of dietary effects in all animals prior to surgery (Supplemental Table S1 and Fig. 1C). In summary, ablation of CD36 protects against WTD-related cardiac dysfunction.

![Graphs and images](E622 CD36 AND INTERACTING STRESSES IN CARDIOMYOPATHY)

**Fig. 4.** Metabolic and inflammation alterations; mRNA expression of pyruvate dehydrogenase kinase-4 (Pdk4; A) and peroxisome proliferator-activated receptor-α (PPARα; B) 6 wk after TAC. HPRT was used as a housekeeping gene. Protein presence of TNFα (C), quantitation of macrophage infiltration in LV sections by Mac3 staining (D), and images of Mac3 staining scored (E; − − (example from CD36<sup>−/−</sup> chow TAC) and ++ (example from WT WTD sham), all 6 wk after TAC (Mac3 staining was scored on a 5-point scale; all image fields were evaluated, and the amount of cells stained by Mac3 were counted: − − is the lowest amount of staining and ++ is the highest amount of staining). Data are means ± SE from 6 to 8 mice in each group. Open bars, control group; light gray bars, metabolic stress (WTD, CD36<sup>−/−</sup> or combination); gray bars, mechanophysical stress (TAC); dark gray bars, interaction of stresses. Statistical analysis was done by 2-way ANOVA. *P < 0.05 vs. WT chow; $vs. sham. Arrows are directed toward Mac3-stained cells (red/pink, with a dark nucleus).
Parameters of cardiac remodeling. Six weeks after TAC surgery, WT mice on chow showed marked signs of cardiac remodeling compared with sham-operated mice. Specifically, after TAC surgery, WT mice on chow showed increments in heart weight (1.44-fold, \( P < 0.05 \); Supplemental Table S2), LV/tibia length (TL) (1.47-fold, \( P < 0.05 \); Fig. 3A), and cardiomyocyte cross-sectional area (1.38-fold, \( P > 0.05 \); Fig. 3B). Even more pronounced cardiac hypertrophy was observed after TAC surgery in the WT mice receiving WTD (vs. sham: LV/TL; 1.87-fold, \( P < 0.001 \)) and CD36\(^{-/-}\) mice receiving chow (vs. sham: LV/TL; 1.71-fold, \( P < 0.001 \)) (Fig. 3A). The combination of WTD and CD36 ablation protected the hearts from TAC-related development of more pronounced cardiac hypertrophy, as observed in WT mice on WTD and CD36\(^{-/-}\) mice on a chow diet. All these changes in LV/TL were also reflected in alterations in cardiomyocyte cross-sectional area (Fig. 3B). Compared with sham-operated mice, TAC increased mRNA expression of atrial natriuretic factor (ANF) in heart tissue from chow- and WTD-fed WT mice 5.4- and 7.6-fold (both \( P < 0.05 \), respectively), and the increase was even more marked in CD36\(^{-/-}\)/chow mice (9.1-fold, \( P < 0.01 \); Fig. 3C). Only CD36\(^{-/-}\) mice receiving a WTD showed no alteration in ANF mRNA expression after TAC surgery. In sham-operated mice there was no effect of either diet or genotype on the above-mentioned parameters of cardiac hypertrophy (Fig. 3, A–C). In summary, ablation of CD36 protects against cardiac remodeling.

Molecular alterations underlying cardiac dysfunction. We investigated several genes that are important in cardiac metabolism and hypertrophy. Pyruvate dehydrogenase kinase-4 (Pdk4) is important in glucose metabolism; peroxisome proliferator-activated receptor-\(\alpha\) (PPAR\(\alpha\)) and acyl-CoA synthetase are involved in fatty acid metabolism, whereas ANF is regulated by cardiac hypertrophy. mRNA expression of Pdk4 was decreased by 78% (\( P < 0.05 \)) in hearts from CD36\(^{-/-}\) mice (Fig. 4A). In addition, PPAR\(\alpha\) mRNA expression changed only upon CD36 ablation; its expression increased compared with WT expression levels (\( P < 0.01 \); Fig. 4B). Administration of a WTD increased cardiac mRNA expression of the PPAR\(\alpha\) response gene acyl-CoA synthetase (\( P < 0.001 \); Fig. 5). In this way, the increased influx of fatty acids is directed rapidly to their metabolic destination, and the cells are protected from the detergent effects of excess fatty acid levels (15). Cardiac mRNA expression of Pdk4 and PPAR\(\alpha\) was not altered by WTD or by TAC (Fig. 4, A and B).

Cardiac protein expression of fatty acid transporter (FATP)1, FATP6, and plasmaemmal fatty acid binding protein were not altered in CD36\(^{-/-}\) mice compared with WT mice (Fig. 5). Additionally, compared with WT chow sham mice, WTD administration and/or TAC did not change the protein expression of any fatty acid transporter including CD36 (Fig. 5).

We measured carnitine palmitoyltransferase I (CPT I) mRNA expression and protein expression of oxidative phosphorylation (OxPhos) proteins to determine possible alterations in mitochondrial oxidation and metabolic inflexibility. mRNA expression of CPT I (Fig. 6), the rate-limiting enzyme in mitochondrial \(\beta\)-oxidation, and protein expression of mitochondrial ATP synthase and complex II in the electron transport chain (Fig. 6) were not changed upon CD36 ablation, WTD administration, or TAC surgery. The other OxPhos complexes showed the same lack of changes (data not shown).

Inflammation is known to influence the development of cardiac dysfunction. (36) Both cardiac protein levels of the proinflammatory cytokine tumor necrosis factor-\(\alpha\) (TNF\(\alpha\)) as presence of macrophages in LV sections were upregulated after TAC in WT mice on both diets compared with CD36\(^{-/-}\) mice (Fig. 4, C–E). In sham-operated mice there was no effect of genotype or diet on TNF\(\alpha\) protein expression (Fig. 4, C–E),
The effects of WTD and CD36 ablation on intramyocardial levels of TG, DG, and ceramide were similar in TAC compared with sham-operated mice. Lower ceramide levels could result in attenuated formation of toxic aldehydes such as 4HNE. We have measured 4HNE levels by Western blotting but did not find differences between any of the groups (Supplemental Fig. S1). In summary, ablation of CD36 protected against WTD-related increase in cardiac lipid content.

**DISCUSSION**

Here we demonstrate for the first time that metabolic stress appears to be an important denominator for TAC-induced mechanophysical stress to become evident. The deleterious effect of WTD-induced metabolic stress on TAC-induced cardiac remodeling and dysfunction was prevented by ablation of the fatty acid transporter CD36. Furthermore, we revealed a tight association between intramyocellular lipid content and decreased cardiac function.

**Effects of metabolic stress on cardiac morphology and function.** WTD resulted in a 1.7-fold increase in cardiac lipid content in WT mice (Fig. 7), and a similar degree of lipid accumulation as found in rats exposed to a similar diet for 10 wk (32). However, WTD did not induce cardiomyopathy (Figs. 2 and 3).

WTD is known to cause a permanent relocation of CD36 to the sarcolemma and increased CD36-mediated fatty acid uptake into the heart (1, 9, 32). In the present study, WTD administration was not accompanied by increased expression of CD36 or of other fatty acid transporters (Fig. 5). Previous studies showed that a twofold increase of FATP1 in hearts from CD36−/− mice did not result in enhanced fatty acid uptake in contraction-stimulated cardiomyocytes (18), suggesting that increased FATP expression cannot alter fatty acid uptake in the working heart.

A recent study showed that excessive cardiac lipid accumulation, induced by PPARα overexpression, is a major causal factor for the development of cardiomyopathy (46). Ablation of CD36 proved to be protective against intramyocellular TG accumulation and cardiomyopathy. However, in our study WTD exposure did not alter PPARα gene expression in WT mice or CD36−/− mice, which strengthens our idea that PPARα overexpression is a less physiological model to induce cardiac lipid oversupply than the use of a WTD.

CD36 ablation causes a metabolic stress opposite of that elicited by WTD, an undersupply of lipids to the heart (12, 18, 26). Accordingly, we showed that accumulation of myocardial lipids and Pdk4 expression were markedly reduced by CD36 ablation, indicating that CD36-ablated hearts rely more on glucose metabolism than do WT hearts. However, CD36−/− mice had no cardiac phenotype. In line with this, transgenic mice with cardiospecific overexpression of the glucose transporter GLUT1 exhibited reduced intramyocellular lipid content without changes in cardiac function (28).

In addition, the excessive intramyocellular lipid accumulation upon a WTD was effectively prevented by CD36 ablation.

In summary, both a WTD and CD36 ablation evoked metabolic stress on the heart, resulting in altered intramyocellular lipid concentrations compared with WT mice on a Chow diet, these changes did not result in altered cardiac function.

**Fig. 6.** Alterations in mitochondrial genes and proteins. mRNA expression levels of carnitine palmityltransferase I (CPT I) measured by RT-PCR (A) and oxidative phosphorylation (OxPhos) protein levels (B and C), measured by Western blotting, all 6 wk after TAC. Data are means ± SE from 6 to 8 mice in each group. White bars, control group; light gray bars, metabolic stress (WTD, CD36 ablation, or combination); gray bars, mechanophysical stress (TAC); dark gray bars, interaction of stresses. Statistical analysis was done by 2-way ANOVA. *P* < 0.05.

In conclusion, CD36 ablation protects against TAC-related increase of inflammation.

**Intramyocardial lipid concentrations.** In sham-operated mice, WT mice receiving a WTD showed higher cardiac TG (1.7-fold, *P* < 0.05), DG (1.4-fold, *P* < 0.05), and ceramide (1.8-fold, *P* < 0.05) contents than WT mice receiving Chow. This confirms that WTD promotes intramyocardial lipid accumulation (Fig. 7, A–C). Sham-operated CD36−/− mice receiving Chow showed lower intramyocardial TG (−32%, *P* < 0.05) and DG (−34%, *P* < 0.05) than sham-operated WT mice on a Chow diet. WTD exposure in sham-operated CD36−/− mice resulted in less intramyocardial TG (1.6-fold, *P* < 0.05) and DG (1.5-fold, *P* < 0.05) accumulation and prevented ceramide accumulation compared with sham-operated WT mice receiving WTD. TAC increased intramyocardial TG, DG, and ceramide levels (Fig. 7, A–C) (1.2- to 1.6-fold, all *P* < 0.05). The effects of WTD and CD36 ablation on intramyocardial levels of TG, DG, and ceramide were similar in TAC compared with sham-operated mice. Lower ceramide levels could result in attenuated formation of toxic aldehydes such as 4HNE. We have measured 4HNE levels by Western blotting but did not find differences between any of the groups (Supplemental Fig. S1). In summary, ablation of CD36 protected against WTD-related increase in cardiac lipid content.
Effects of mechanophysical stress on cardiac morphology and function. TAC has been reported to increase LV pressure, to induce cardiac remodeling (20), and to provoke alterations in substrate utilization (35). In WT mice on a chow diet, we detected a 30% increase in cardiac mass due to hypertrophic growth of cardiomyocytes 6 wk after TAC. This was accompanied by a large upregulation of ANF expression. However, this degree of hypertrophy was apparently insufficient to result in decreased function. Additionally, TAC had little or no effect on cardiac metabolic parameters, induced a slight increase in intramyocellular lipid concentrations, and did not affect gene and protein expression levels of enzymes and transporters important in substrate utilization (Figs. 4–7).

In summary, TAC induced mechanophysical stress on the heart, resulting in adaptive cardiac remodeling accompanied by only minor changes in cardiac lipid content.

Interaction between metabolic and mechanophysical stress. Patients displaying obesity and hypertension often suffer from impaired cardiac function. In our mouse model we tried to mimic this combination by starting the mice on a WTD and performing TAC afterward to induce pressure overload. We found that TAC in combination with a metabolic stress (either WTD or CD36 ablation) evoked a greater cardiac hypertrophy than TAC alone. Importantly, this greater cardiac hypertrophy was accompanied by loss of function as measured by LVESD and FS. This shows that metabolic stress, by itself not affecting cardiac function, aggravates the effect of mechanophysical stress on cardiac function.

In a previous study, C57Bl/6 mice were exposed to a WTD or a standard diet after TAC surgery, which did not affect cardiac function (2, 7). However, in that study the role of existing cardiac metabolic stress interacting with cardiac remodeling and dysfunction was not studied. Here, we show that existing metabolic stress interacts with later-induced cardiac mechanophysical stress.

Absence of CD36 protects against interaction of stresses. To test our hypothesis that CD36 ablation could modify the interaction between metabolic and mechanophysical stress, we evaluated whether the TAC-induced cardiac dysfunction and greater cardiac remodeling that we had observed in WT mice exposed to a WTD were altered by CD36 ablation. Interestingly, CD36<sup>−/−</sup> mice that underwent TAC surgery during WTD administration did not develop cardiac dysfunction, nor did they develop adverse cardiac remodeling as observed in WT mice on a chow diet. Moreover, CD36 ablation prevented the WTD-induced intramyocellular lipid accumulation in TAC-treated mice. Intramyocellular lipid alteration alone did not affect cardiac function and morphology, but it augmented hypertrophic growth of the heart and development of cardiac dysfunction in response to pressure overload. This shows that when lipid accumulation is prevented by CD36 ablation, thus eliminating metabolic stress, mechanophysical stress is no longer able to affect cardiac function.

Inflammation is known to worsen the progression toward cardiac dysfunction (6). We observed that 6 wk after TAC the proinflammatory cytokine TNFα and the presence of macrophages in LV sections were upregulated only in WT mice. This relates to the observations of Collot-Teixeira et al. (8) and Kennedy et al. (24), who found in mice adipocytes and macrophages that CD36 is needed for signaling to genes coding for an inflammatory response. This suggests that, in the heart, ablation of CD36 prevents not only fatty acid uptake but also a detrimental inflammatory reaction.

It has become increasingly evident that mitochondrial dysfunction is an important mechanism contributing to the metabolic cardiomyopathy phenotype (5). We observed that neither CPT I gene expression nor protein expression of ATP synthase and complex II of the electron transport chain was altered as a result of any of the stressors used. Although we did not measure mitochondrial oxidation, these observations suggest that cardiac mitochondrial function was not severely affected by the exposure to intramyocardial lipid levels resulting from WTD, CD36 ablation, or TAC.

Conclusions. In the presence of a mechanophysical stress, a decrease of 32% in intramyocardial lipid levels in CD36<sup>−/−</sup> mice and an increase of 1.7-fold in intramyocardial lipid levels in WT mice elicited by WTD are associated with impaired cardiac functioning. Combining these two observations alludes to the conclusion that, for the compromised heart, the intramyocardial lipid content should be maintained within a narrow range to maintain cardiac function. Taken together, the intramyocardial milieu, especially the lipid concentration, is a crucial factor to determine the detrimental effects of TAC on cardiac function.
Although WTD and CD36 ablation each interact with TAC in the development of cardiac dysfunction, the combination of these interventions did not impair cardiac function. On the contrary, they counterbalanced each other, thereby revealing the metabolic origin of these cardiac diseases. These metabolic roots of cardiac dysfunction (33) imply that treatment strategies should have a metabolic character. Because prevalence of the metabolic syndrome and type 2 diabetes are rising, inhibition of CD36 can be a potential approach for treatment of metabolic cardiomyopathy.

ACKNOWLEDGMENTS

We thank L. Keersmaekers and L. Ding for their excellent technical assistance and Biomedic for lending us the Aloka Terason 3000cv.

GRANTS

This work was supported by the Dutch Diabetes Research Foundation (Grant no. 2006.00.044) and by The Netherlands Organization for Health Research and Development (NWO-ZonMw) (Grant no. 912-04-075). O. C. M. Vroegrijk is supported by the 7th FP of the European Union (Grant no. 2006.00.044) and by The Netherlands Organization for Health Research and Development (NWO-ZonMw) (Grant no. 912-04-075).

DISCLOSURES

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