

Inactivation of peroxisome proliferator-activated receptor isoforms α , β/δ , and γ mediate distinct facets of hypertrophic transformation of adult cardiac myocytes

Corinne Pellieux · Christophe Montessuit ·
Irène Papageorgiou · René Lerch

Received: 7 March 2007 / Revised: 30 April 2007 / Accepted: 16 May 2007 / Published online: 21 July 2007
© Springer-Verlag 2007

Abstract Inactivation of peroxisome proliferator-activated receptor (PPARs) isoforms α , β/δ , and γ mediate distinct facets of hypertrophic transformation of adult cardiac myocytes. PPARs are ligand-activated transcription factors that modulate the transcriptional regulation of fatty acid metabolism and the hypertrophic response in neonatal cardiac myocytes. The purpose of this study was to determine the role of PPAR isoforms in the morphologic and metabolic phenotype transformation of adult cardiac myocytes in culture, which, in medium containing 20% fetal calf serum, undergo hypertrophy-like cell growth associated with downregulation of regulatory proteins of fatty acid metabolism. Expression and DNA-binding activity of PPAR α , PPAR β/δ , and PPAR γ rapidly decreased after cell isolation and remained persistently reduced during the 14-day culture period. Cells progressively increased in size and developed both re-expression of atrial natriuretic factor and downregulation of regulatory proteins of fatty acid metabolism. Supplementation of the medium with fatty acid (oleate 0.25 mM/palmitate 0.25 mM) prevented inactivation of PPARs and downregulation of metabolic genes. Furthermore, cell size and markers of hypertrophy were markedly reduced. Selective activation of either PPAR α or PPAR β/δ completely restored expression of regulatory genes of fatty acid metabolism but did not influence cardiac myocyte size and markers of hypertrophy. Conversely, activation of PPAR γ prevented cardiomyocyte hypertrophy but had no effect on fatty acid metabolism. The results indicate that PPAR activity markedly influences hypertrophic transformation of adult rat cardiac

myocytes. Inactivation of PPAR α and PPAR β/δ accounts for downregulation of the fatty acid oxidation pathway, whereas inactivation of PPAR γ enables development of hypertrophy.

Keywords Metabolism · Genes · Hypertrophy · Phenotype · Cardiomyocyte

Introduction

Phenotypic modification of cardiac myocytes plays a critical role during the development of myocardial hypertrophy and progression to heart failure [25]. A number of observations suggest that morphological and functional changes of cardiac myocytes are associated with modification of transcriptional regulation of substrate metabolism including altered expression of glucose transporter isoforms [32, 36] and downregulation of genes encoding regulatory proteins of fatty acid oxidation [26, 27, 39]. To date, very little is known on the mechanisms linking alterations of the morphologic and metabolic phenotype.

Peroxisome proliferator-activated receptors (PPARs) are nuclear receptor transcription factors that are activated by fatty acid derivatives and, therefore, may modify the cellular phenotype in response to alteration of cytoplasmic fatty acid concentration [16, 44]. PPARs bind to the DNA consensus response element as obligate heterodimers with retinoid X receptor (RXR) [16]. All three presently known isoforms, PPAR α , PPAR β/δ , and PPAR γ , are expressed in cardiac myocytes [14, 16]. PPAR α and PPAR β/δ play a central role in the transcriptional regulation of fatty acid oxidation [14]. In fact, PPAR α -deficient mice [46] and mice with cardiac-myocyte-restricted deletion of PPAR β/δ in the heart [5] exhibit marked reduction of fatty acid oxidation enzymes in the myocardium and a corresponding

C. Pellieux (✉) · C. Montessuit · I. Papageorgiou · R. Lerch
Department of Internal Medicine, Cardiology Center,
University Hospitals of Geneva,
24, rue Micheli-du-Crest, CH-1211,
Geneva 14, Switzerland
e-mail: corinne.pellieux@hcuge.ch

decrease of fatty acid oxidation. Observations in animal models have implicated inactivation of PPAR α signaling in the downregulation of fatty acid oxidation enzymes during overload-induced myocardial hypertrophy and heart failure [2, 19, 48]. In adipocytes, PPAR γ is involved in the expression of enzymes of synthesis of fatty acids and triglycerides [16], but its role in cardiac myocytes is still poorly defined.

Studies in neonatal rat cardiac myocytes suggest that PPAR signaling not only influences regulation of fatty acid metabolism but also may modify the hypertrophic response. Selective activation of either PPAR α [17, 21], PPAR β/δ [30], or PPAR γ [47] reduced protein synthesis in neonatal cardiac myocytes exposed to phenylephrine [30, 47], angiotensin II [47], endothelin-1 [17, 21], or mechanical strain [47]. Cell size and expression of atrial natriuretic factor was reduced concomitantly [1, 21, 47]. These observations are compatible with the hypothesis that inactivation of PPAR α , and possibly of other PPAR isoforms, may not only mediate downregulation of the fatty acid oxidation pathway, but also contribute to cardiac myocyte hypertrophy and dedifferentiation during maladaptive remodeling. However, the role of individual PPAR isoforms in the modification of the morphologic and metabolic phenotype has not been studied in adult cardiac myocytes.

In the present study, we investigated the role of PPAR expression and activity in the phenotypic modification of adult rat cardiac myocytes (ARC) in long-term culture. ARC cultured in medium containing 20% fetal calf serum (FCS) undergo phenotypic transformation that exhibits similarities to that observed during the development of maladaptive hypertrophy and heart failure in vivo [41]. The changes include cellular spreading, re-expression of “immature” isoforms of contractile proteins, and re-expression of so-called fetal genes [9, 12, 22]. We have previously observed that the phenotypic modification of ARC is associated with the return to a fetal-like expression pattern of metabolic genes. There occurs a shift from glucose transporter-4 (GLUT4) to glucose transporter-1 (GLUT1) [23, 35], and downregulation of messenger RNA (mRNA) expression of a number of regulatory genes of fatty acid oxidation [37]. We hypothesized that hypertrophy-like phenotype transformation and downregulation of the fatty acid oxidation pathway is associated with inactivation of PPAR signaling.

Materials and methods

The investigation conforms to the *Guide for the Care and Use of Laboratory Animals* published by the US National Institutes of Health (NIH publications no. 85–23, revised

1996) and was approved by the local animal protection authorities.

Cell isolation and culture

ARC were isolated from male oncins France strain A (OFA) rats (Charles River, France) weighing 110–120 g by retrograde perfusion of the hearts with collagenase (Worthington Biochemical) as described previously [13, 23]. After preplating in uncoated dishes (2 h; 37°C) to remove non-myocyte cells, cardiac myocytes were plated onto dishes coated with 0.1% gelatin. The culture medium was M199 supplemented with 20% (vol/vol) FCS (Invitrogen), 1% penicillin/streptomycin, and 20 mmol/l creatine throughout the culture period. To avoid proliferation of residual non-myocyte cells, 10 μ mol/l 1- β -D-arabinofuranosyl-cytosine was added to the culture medium. More than 90% of the cells were myocytes upon visual inspection at light microscopy after each culture interval with increasing purity over time. The standard culture medium contained glucose (5.5 mmol/l). In selected experiments, palmitate and oleate at equimolar concentration (0.25 mmol/l each, unless otherwise stated) were added to the culture medium throughout the entire culture period. Fatty acids were prebound to serum albumin (0.2 mmol/l) as described previously [8]. Unlike palmitate alone, palmitate plus oleate does not elicit apoptosis in ARC [11]. PPAR isoforms were selectively activated with the PPAR α ligand WY-14643 (100 nmol/l; Biomol), the PPAR β/δ ligand L 165–041 (1 μ mol/l; Fluka), or the PPAR γ ligand ciglitazone (10 nmol/l; Biomol). PPAR agonists were dissolved in dimethyl sulphoxide (DMSO), which was also added (0.1% vol/vol) to the control cells.

Immunofluorescence and cell surface area determination

ARC were fixed with 4% paraformaldehyde in phosphate-buffered saline (PBS) and permeabilized with 0.3% Triton X-100 in PBS. Primary antibody against sarcomeric α -actinin (Sigma) was recognized by an anti-mouse IgG-FITC-conjugated antibody (Sigma). Counterstaining for F-actin was obtained with rhodamine-phalloidin (Molecular Probes, Eugene) and DNA staining with 4',6-diamidino-2-phenylindole (DAPI; Molecular Probes). Slides were mounted with VectaShield (Vector Laboratories) and examined using a Carl Zeiss Axiophot microscope equipped with an Axiocam color charge-coupled device (CCD) camera (Carl Zeiss). Images were acquired with the AxioVision software (Carl Zeiss) and processed with Photoshop 3.0.5 (Adobe Systems).

Relative cell surface area was calculated from digitized cardiac myocyte images taken from random fields of view using NIH Image software (version 1.62). At least 100 cells

were measured for each condition by an observer blinded to the culture conditions.

Protein extraction and western blot

Cells were homogenized in lysis buffer containing Tris–HCl 10 mmol/l, NaCl 150 mmol/l, and ethylenediaminetetraacetic acid (EDTA) 1 mmol/l, Igepal 1%, sodium deoxycholate 0.5%, sodium dodecyl sulfate (SDS) 0.1%, and protease inhibitor cocktail (Roche). Proteins (100 µg) were loaded onto 8.5% SDS polyacrylamide gel electrophoresis (SDS–PAGE) gels. Ponceau's red staining was performed to verify equal loading. Western blot analysis was performed using polyclonal antibodies against PPAR α and PPAR γ (Santa Cruz Biotechnology), PPAR β/δ (Cayman chemicals), fatty acid translocase (FAT/CD36; Santa Cruz Biotechnology), medium-chain acyl-CoA dehydrogenase (MCAD; Cayman Chemicals), and muscle-type carnitine palmitoyltransferase-I (mCPT-I; a gift from Dr. Gebre Woldegiorgis). Antibodies were diluted in Tris-buffered saline containing 0.1% Tween 20. All antibodies identified the proper protein band. Specific signals were detected by chemiluminescence (ECL, Amersham) and quantified by laser densitometry (Imagequant 3.3, Molecular Dynamics).

DNA-binding activity of PPAR

DNA-binding activities of PPAR α and PPAR γ were measured in nuclear extracts prepared as described previously [23] using an enzyme-linked immunosorbent assay (ELISA) assay (Active Motif). Briefly, active PPARs in nuclear extracts bind specifically to consensus oligonucleotides coated on a well plate and are detected using an antibody directed against PPAR. Addition of a secondary antibody conjugated to horseradish peroxidase provides a sensitive colorimetric readout that is quantified by spectrophotometry.

RNA extraction and quantitative reverse transcription-polymerase chain reaction

Total RNA was purified using Trizol reagent. After DNase (Invitrogen) treatment, RNA was analyzed by reverse transcription (Superscript II, Invitrogen) followed by real-time quantitative polymerase chain reaction (PCR; TaqMan, BioRad). The rat nucleotide sequences of probes, as well as of forward and reverse primers, were designed from unconserved sequences of the genes, allowing isoform specificity (Table 1). The transcripts of the constitutive housekeeping gene product cyclophilin were quantitatively measured in each sample, and PCR data were reported as the number of transcripts per cyclophilin transcript. Cycle number for cyclophilin was virtually identical in ARC cultured for 14 days (27.5 ± 2.0 cycles/ μgRNA) and in freshly isolated

ARC (27.5 ± 1.8 cycles/ $\mu\text{g RNA}$), indirectly suggesting expression stability over time. Furthermore, identical results to normalization by cyclophilin were obtained using 18S ribosomal RNA (rRNA) as housekeeping gene.

Palmitate oxidation

Palmitate oxidation was estimated based on the release of $^{14}\text{CO}_2$ from [$1\text{-}^{14}\text{C}$]-palmitate (Amersham). For measurement of palmitate oxidation, cells were incubated for 60 min in sealed flasks containing a suspended filter paper soaked with an organic base (NCS-II, Amersham) and medium containing palmitate (0.05 mmol/l), oleate (0.05 mmol/l), and 1 $\mu\text{Ci/ml}$ [$1\text{-}^{14}\text{C}$]-palmitate. All fatty acids were complexed to bovine serum albumin (0.2 mmol/l). The reaction was stopped by addition of 2N perchloric acid. $^{14}\text{CO}_2$ produced by [$1\text{-}^{14}\text{C}$]-palmitate metabolism was collected overnight on the filter paper and quantified by scintillation counting.

Table 1 Primers of RT-PCR assays. F: forward primer, R: reverse primer, P: probe

Genes		Primers and probe sequences
Cyclophilin	F	5'-CTG ATG GCG AGC CCT TG-3'
	R	5'-TCT GCT GTC TTT GGA ACT TTG TC-3'
	P	5'-CGC GTC TGC TTC GAG CTG TTT GCA-3'
ANF	F	5'-AGT GCG GTG TCC AAC ACA G-3'
	R	5'-CTT CAT CGG TCT GCT CGC T-3'
	P	5'-TCT GAT GGA TTT CAA GAA CCT GCT AGA CCA-3'
BNP	F	5'-AAG TCC TAG CCA GTC TCC A-3'
	R	5GTC TCT GAG CCA TTT CCT C-3'
	P	5'-GCA GAA GCT GCT GGA GCT GAT AA-3'
PPAR α	F	5'-ACT ACG GAG TTC ACG CAT GTG-3'
	R	5'-TTG TCG TAC ACC AGC TTC AGC-3'
	P	5'-AGG CTG TAA GGG CTT CTT TCG GCG-3'
PPAR β/δ	F	5'-TGG ATA CGC TTC ACA GTC C-3'
	R	5'-GCA GGC TCT AGA ATT CCA TC-3'
	P	5'-ACC TGC GGC AGC TGG TCA CTG A-3'
PPAR γ	F	5'-CCA TTC TGG CCC ACC AAC-3'
	R	5'-AAT GCG AGT GGT CTT CCA TCA-3'
	P	5'-TCG GAA TCA GCT CTG TGG ACC TCT CC-3'
FAT/CD36	F	5'-TCC AGC CAA TGC CTT TGC-3'
	R	5'-TGG AGA TTA CTT TTC AGT GCA GAA-3'
	P	5'-TCA CCC CTC CAG AAT CCA GAC AAC CA-3'
MCAD	F	5'-TGG CAT ATG GGT GTA CAG GG-3'
	R	5'-CCA AAT ACT TCT TCT TCT GTT GAT CA-3'
	P	5'-AGG CAT TTG CCC CAA AGA ATT TGC TTC-3'
mCPT-I	F	5'-ATC ATG TAT CGC CGC AAA CT-3'
	R	5'-ATC TGG TAG GAG CAC ATGG GT-3'
	P	5'-TCA AGC CGG TAA TGG CAC TGG G-3'

[³H]-Phenylalanine incorporation

To obtain an index for the rate of de novo protein synthesis, ARC were incubated after selected culture intervals for 2 h at 37°C in serum-free M199 containing 2 μCi/ml of L-[2,3,4,5-³H]phenylalanine (Amersham) with or without PPAR agonists. At the end of the incubation period, the culture medium was removed, and cardiac myocytes were rinsed three times with ice-cold PBS. DNA and protein were precipitated by trichloroacetic acid and transferred into 0.3-M sodium hydroxide. [³H]-Phenylalanine incorporation and DNA content were determined as reported previously [34]. [³H]-phenylalanine incorporation was normalized to nanograms of DNA per sample. Results are expressed as percentage of the mean value measured in freshly isolated ARC cultured for measurement of [³H]-phenylalanine incorporation in standard medium.

Statistics

Results are obtained from at least three independent experiments and expressed as mean±SEM. Mean group values were compared by analysis of variance (ANOVA; Prism 4), applying Bonferroni's adjustment for multiple comparisons. *P* values <0.05 were considered significant.

Results

Fatty acid supplementation of culture medium prevents ARC hypertrophy and downregulation of mRNA expression of regulatory proteins of fatty acid metabolism

ARC cultured in medium containing 20% FCS underwent morphological remodeling as described previously [12, 23]. After 3–4 days of culture, cells resumed spontaneous beating

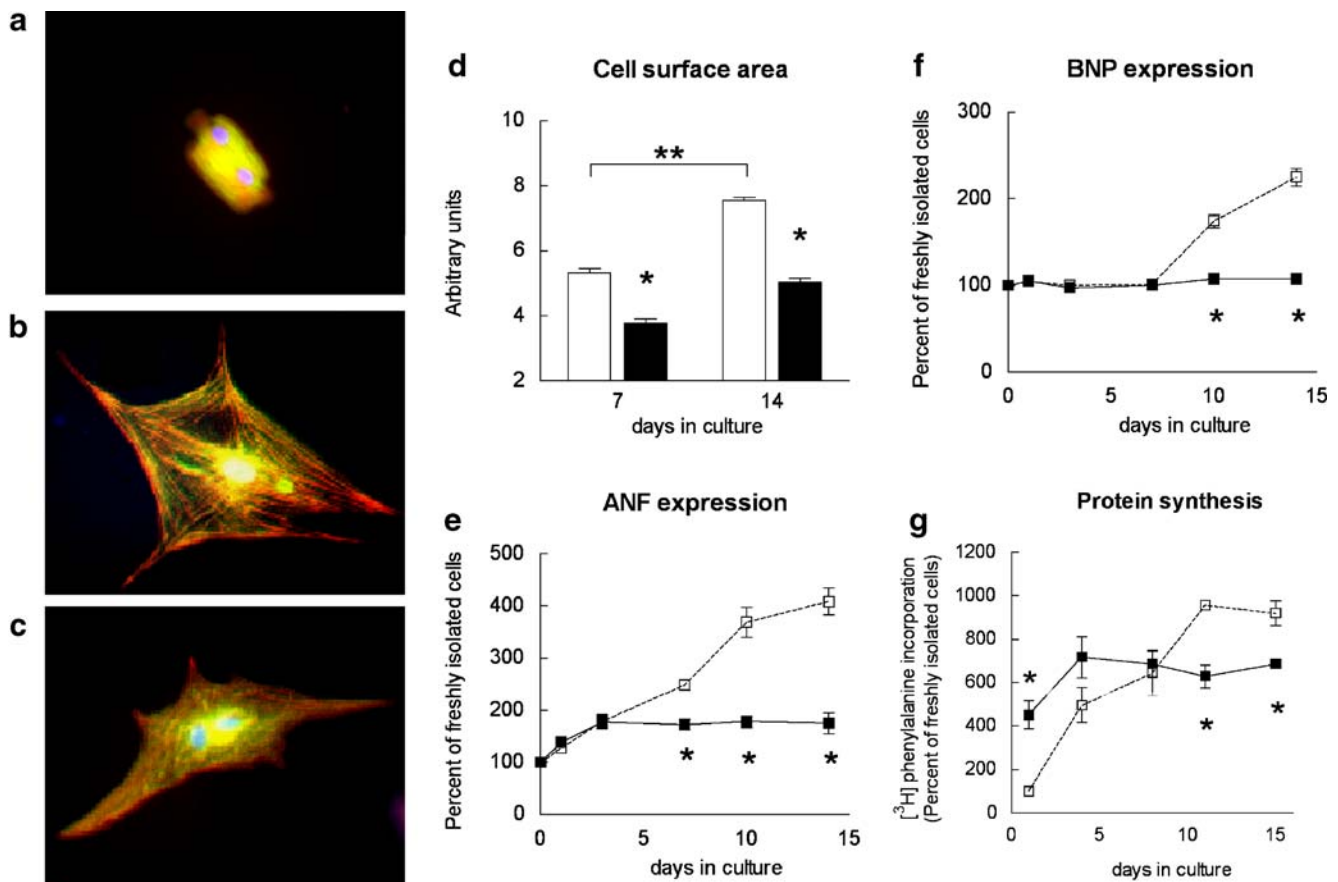


Fig. 1 Effect of supplementation of the culture medium with fatty acid (oleate 0.25 mmol/l/palmitate 0.25 mmol/l) on cardiac myocyte size and ANF expression. **a** Freshly isolated cardiac myocyte. After 14 days of culture in medium containing 20% FCS, cardiac myocytes had increased in size and assumed a polymorphic shape (**b** and **c**). Cells cultured in fatty-acid-free medium were larger (**b**) than in medium containing oleate/palmitate (**c**). *Green* α -Actinin, *blue* nucleus, and *red* phalloidine. **d** Relative difference of cell size estimated by planimetry on days 7 and 14 (control, *open bars*; fatty acid, *filled bars*; at least 100 cells in three to six different cultures were

measured for each condition). **e** and **f** Change in ANF and BNP mRNA expression relative to freshly isolated cardiac myocytes (*n*=6 for each condition). ANF (**e**) and BNP (**f**) expression were markedly lower in cells cultured during 14 days with fatty acids (*filled squares*) compared with those cultured without fatty acids (*open squares*). **g** De novo protein synthesis, estimated from [³H]-phenylalanine incorporation (*n*, at least four independent experiments), increased throughout the culture period (*open squares*) and was attenuated by fatty acids (*filled squares*). Values are means±SEM. **P*<0.05 compared with “without fatty acid.” ***P*<0.05 between indicated groups

and continuously increased in size throughout the 14-day culture period (Fig. 1a–d). The rate of de novo protein synthesis, estimated from [^3H]-phenylalanine incorporation, also continuously increased (Fig. 1g). Moreover, mRNA expression of atrial natriuretic factor (ANF) increased progressively and averaged, after 14 days, $409\pm 25\%$ of the value measured in freshly isolated cardiac myocytes (Fig. 1e). Similarly, brain natriuretic peptide (BNP) mRNA increased to $225\pm 9\%$ ($P<0.05$; Fig. 1f). Supplementation of the culture medium with 0.5 mmol/l fatty acids (palmitate 0.25 mmol/l plus oleate 0.25 mmol/l) during the entire culture period reduced cell spreading with a decrease of cell surface area by 29 and 33% after 7 and 14 days, respectively, compared with cells cultured in standard medium (Fig. 1b–d). The rate of de novo protein synthesis leveled off after 5 days in the presence of fatty acids and remained constant thereafter

(Fig. 1g). Fatty acids markedly attenuated the increase of ANF mRNA (Fig. 1e) and prevented the increase of BNP mRNA, which averaged, after 14 days, $107\pm 14\%$ of the values measured in freshly isolated cardiac myocytes (Fig. 1f). No appreciable effect of fatty acids on contractile function was observed.

We monitored the expression of three PPAR target genes that are involved in the regulation of fatty acid metabolism: fatty acid translocase (FAT/CD36), medium-chain acyl-CoA dehydrogenase (MCAD), and muscle-type carnitine palmitoyltransferase-I (mCPT-I). In standard medium, mRNA expression of MCAD, FAT/CD36, and mCPT-I decreased rapidly after cell isolation to 50 to 70% of values measured in freshly isolated cardiac myocytes and continued to decrease thereafter to 15 to 35% after 14 days (Fig. 2a–c). Interestingly, there was no concomitant decrease of protein expression of

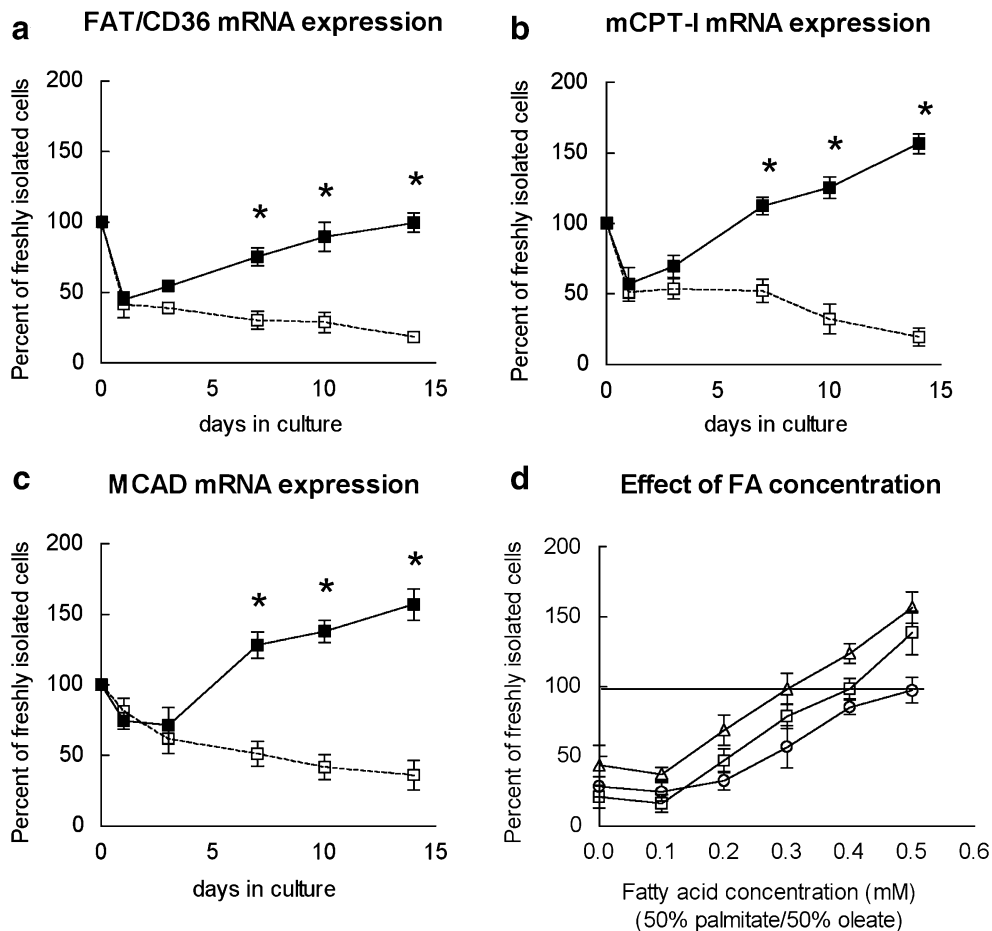


Fig. 2 Effect of supplementation of the culture medium with fatty acids on mRNA expression of regulatory proteins of fatty acid metabolism. mRNA expression of FAT/CD36 (a), mCPT-I (b), and MCAD (c) decreased rapidly after isolation and remained low in cardiac myocytes cultured without fatty acid (open squares). The reduction compared with freshly isolated cardiac myocytes was significant for each culture period ($P<0.05$). In the presence of 0.5 mmol/l fatty acids (oleate 0.25 mmol/l plus palmitate 0.25 mmol/l; filled squares), mRNA expression of all three proteins steadily

increased to supranormal values (n , at least five determinations for each data point). **d** Effect of increasing fatty acid (FA) concentration on mRNA expression of FAT/CD36 (circles), mCPT-I (squares), and MCAD (triangles). Stimulation of mRNA expression was observed at all examined total fatty acid concentrations >0.1 mmol/l. Each fatty acid concentration consisted of equimolar proportions of oleate and palmitate. Values are means \pm SEM. * $P<0.05$ compared with “without fatty acid”

MCAD, FAT/CD36, and mCPT-I after 14 days (Fig. 3a). Likewise, oxidation of palmitate was only slightly reduced by 21% compared with freshly isolated ARC (Fig. 3b).

Supplementation of the medium with fatty acid did not prevent the initial drop of mRNA expression of MCAD, FAT/CD36, and mCPT-I (Fig. 2a–c). However, mRNA expression increased steadily thereafter. Stimulation of mRNA expression was observed at total fatty acid concentrations higher than 0.1 mmol/l (Fig. 2d). In the presence of a total fatty acid concentration of 0.5 mmol/l, values measured after 14 days were equal (FAT/CD36) or higher (mCPT-I, MCAD) than those measured in freshly isolated cardiac myocytes (Fig. 2a–c). Concomitantly, protein expression of MCAD,

FAT/CD36, and mCPT-I was increased roughly by 50% compared with values measured in ARC cultured without fatty acid (Fig. 3a), and oxidation of palmitate was approximately doubled (Fig. 3b).

Reduction of transcriptional activity of PPAR α , PPAR β/δ , and PPAR γ in ARC is restored by fatty acid supplementation

We determined whether the expression and/or DNA-binding activity of PPARs are altered in ARC undergoing phenotypic changes. In ARC cultured in standard medium, mRNA expression levels of PPAR α , PPAR β/δ , and PPAR γ were decreased to less than 50% of the values measured in freshly isolated ARC throughout the entire 14-day culture interval (Fig. 4a). However, protein expression decreased only transiently (day 1) and was restored by day 3 to values comparable to those measured in freshly isolated ARC, without further change up to day 14 (Fig. 4b). DNA-binding activity of PPAR α and PPAR γ (binding activity of PPAR β/δ was not measured) decreased to approximately 50% of values measured in freshly isolated ARC and, in contrast to protein expression, did not appreciably recover thereafter (Fig. 4c and d). Thus, cardiac myocyte remodeling seems to be associated with reduced DNA binding, rather than reduced protein expression of PPAR isoforms.

Supplementation of the culture medium with fatty acids largely restored DNA binding of PPAR α and PPAR γ by day 7 (Fig. 4c and d). mRNA expression of all PPAR isoforms was also restored by fatty acid, showing a similar time course (only data for day 14 displayed; Fig. 4a). This presumably reflects the known presence of PPAR response elements (PPRE) in the promoter region of PPAR genes [30].

Differential effects of PPAR isoforms on metabolic and morphologic phenotype of ARC

To determine the role of individual PPAR isoforms, ARC were treated with specific agonists of either PPAR α (WY-14643), PPAR β/δ (L 165-041), or PPAR γ (ciglitazone). As each PPAR isoform transactivates its own expression, specificity of compounds was validated by measurement of the effect on PPAR mRNA expression in standard medium. At the selected concentration, each agonist selectively restored mRNA expression of the corresponding PPAR isoform to values comparable to those measured in freshly isolated cells (Fig. 5a). DNA-binding activity was measured for PPAR α and PPAR γ . WY-14643 and ciglitazone selectively increased DNA-binding activity of PPAR α and PPAR γ , respectively (Fig. 5b). Thus, the selected agonists selectively activated PPAR isoforms in ARC.

The effect of selective activation of each PPAR isoform on the expression of regulatory genes of fatty acid metabolism

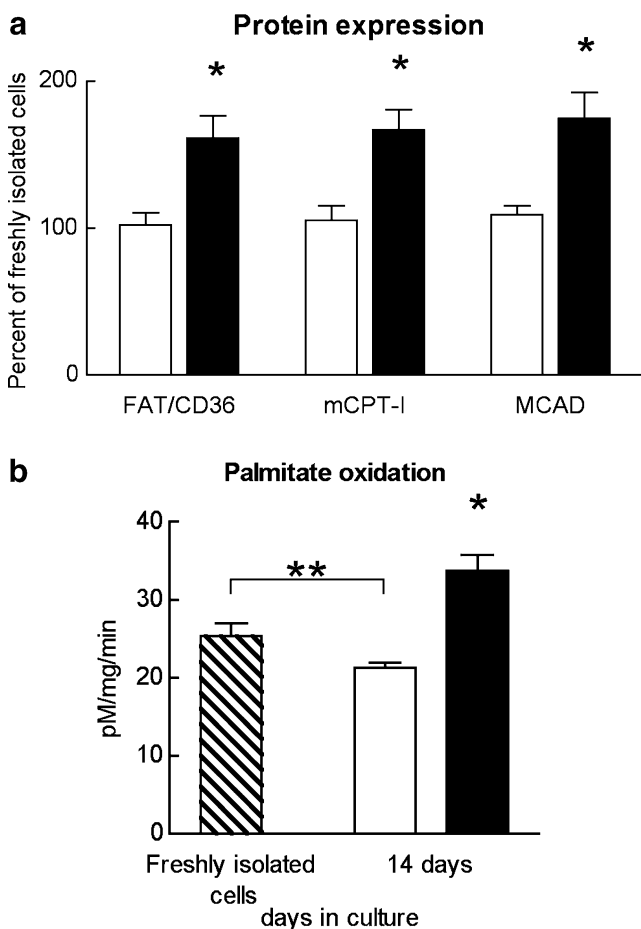


Fig. 3 Effect of supplementation of the culture medium with fatty acids (oleate 0.25 mmol/l plus palmitate 0.25 mmol/l) on protein expression of regulatory proteins of fatty acid oxidation (**a**) and palmitate oxidation (**b**). **a** On day 14, protein expression of FAT/CD36, mCPT-I, and MCAD was approximately 50% higher in ARC cultured with fatty acids (filled bars) compared to ARC cultured without fatty acids (open bars; *n*, at least six determinations for each data point). **b** Palmitate oxidation in cardiac myocytes immediately after isolation (freshly isolated ARC, *n*=6) and in cells cultured for 14 days without (open bar, *n*=5) and with fatty acids (filled bar, *n*=4). Palmitate oxidation was higher in the presence of fatty acids. Values are means \pm SEM. **P*<0.05 compared with “without fatty acid”. ***P*<0.05 between indicated groups

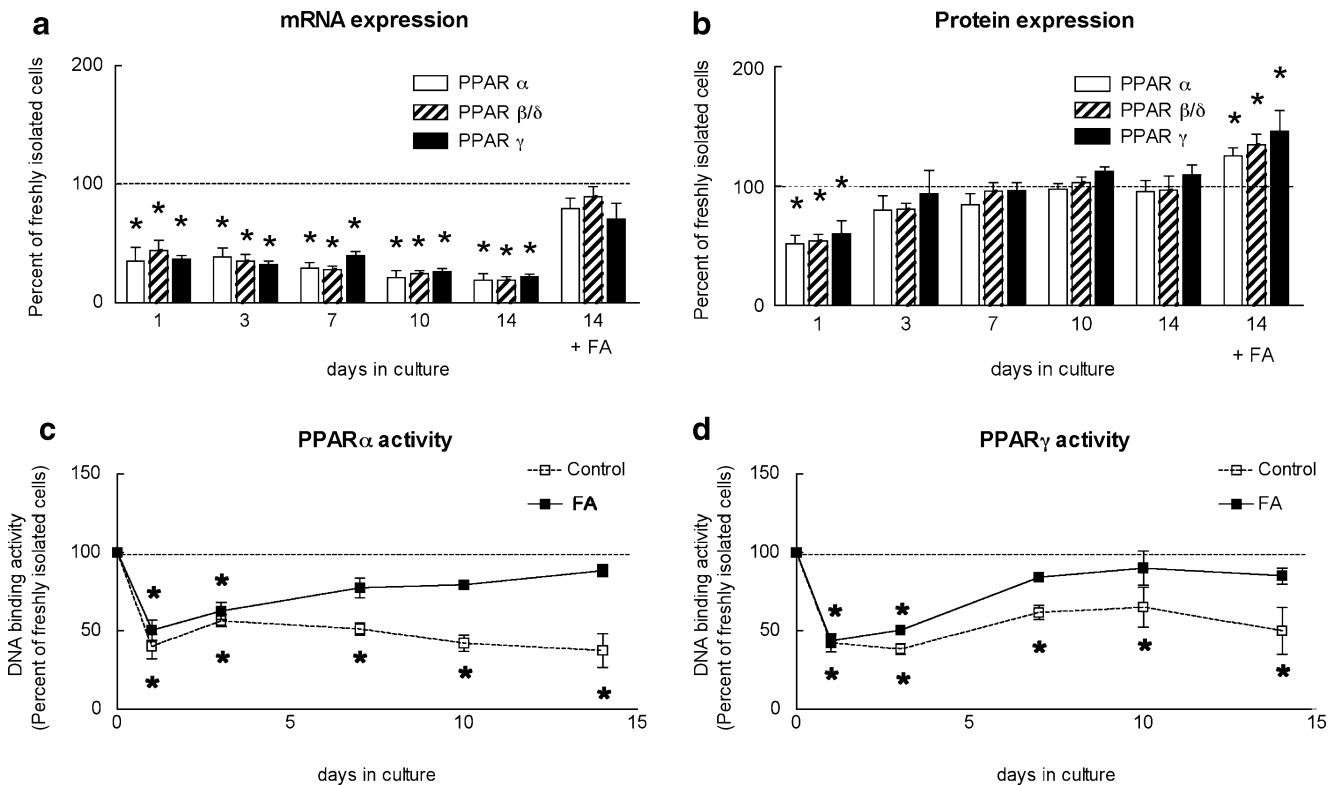


Fig. 4 Changes of expression and DNA-binding activity of PPAR isoforms. In cardiac myocytes cultured in standard medium. mRNA expression by RT-PCR of PPAR α , PPAR β/δ , and PPAR γ (a) was reduced by at least 50% during the entire culture period. In the presence of fatty acids, mRNA expression was not reduced after 14 days. Protein expression (b) dropped only transiently, immediately after isolation, and completely recovered thereafter. DNA-binding

activity (measured by ELISA) of PPAR α (c) and PPAR γ (d) decreased immediately after isolation and remained low in standard medium (open squares). Fatty acid supplementation largely restored DNA-binding activity (filled squares). Values are means \pm SEM of at least three determinations for each data point. * P <0.05 compared with freshly isolated ARC

and hypertrophic markers is shown in Figs. 6 and 7. Activation of PPAR α or PPAR β/δ by WY-14643 or L 165–041, respectively, restored mRNA expression of FAT/CD36, mCPT-I, and MCAD to values comparable to those measured in freshly isolated cardiac myocytes (Fig. 6a–c). Conversely, activation of PPAR γ by ciglitazone had no effect on the expression of genes of fatty acid metabolism (Fig. 6a–c).

Cell surface area of ARC cultured for 14 days in standard medium was significantly reduced by ciglitazone by 37% compared with the control (Fig. 7a). Ciglitazone also decreased the rate of de novo protein synthesis by 22% (Fig. 7c). Furthermore, ciglitazone reduced expression of ANF by 53% (Fig. 7b) and of BNP by 31% (P <0.05). In contrast, WY-14643 and L 165–041 did not alter cell surface area, protein synthesis, expression of ANF, or expression of BNP (Fig. 7a–c).

Discussion

Ventricular myocytes of adult rat hearts cultured in medium containing 20% FCS undergo a progressive remodeling

process. Phenotypic changes include an increase in cell size, acceleration of de novo protein synthesis and re-expression of so-called “fetal genes,” resembling cardiac myocyte hypertrophy in vivo [9, 12, 23, 41]. ARC, therefore, offer a homogenous system for delineating the effects of individual stimuli on the hypertrophic response in terms of gene expression and cell morphology. The present study implicates all three PPAR isoforms expressed in the myocardium in an isoform-specific manner as modulators of the morphologic and metabolic phenotype of adult cardiac myocytes. The results demonstrate in ARC in long-term culture that: (1) the progressive hypertrophic response and the downregulation of genes controlling fatty acid oxidation are associated with inactivation of PPAR α , PPAR β/δ , and PPAR γ at unaltered protein levels; (2) PPAR-inactivation is reversed, and both metabolic and hypertrophic changes are attenuated, by supplementation of the culture medium with fatty acid; and (3) in fatty-acid-free medium, selective activation of PPAR α or PPAR β/δ , but not of PPAR γ , restores expression of regulatory proteins of fatty acid metabolism, without a change of markers of hypertrophy. Conversely, activation of PPAR γ attenuates

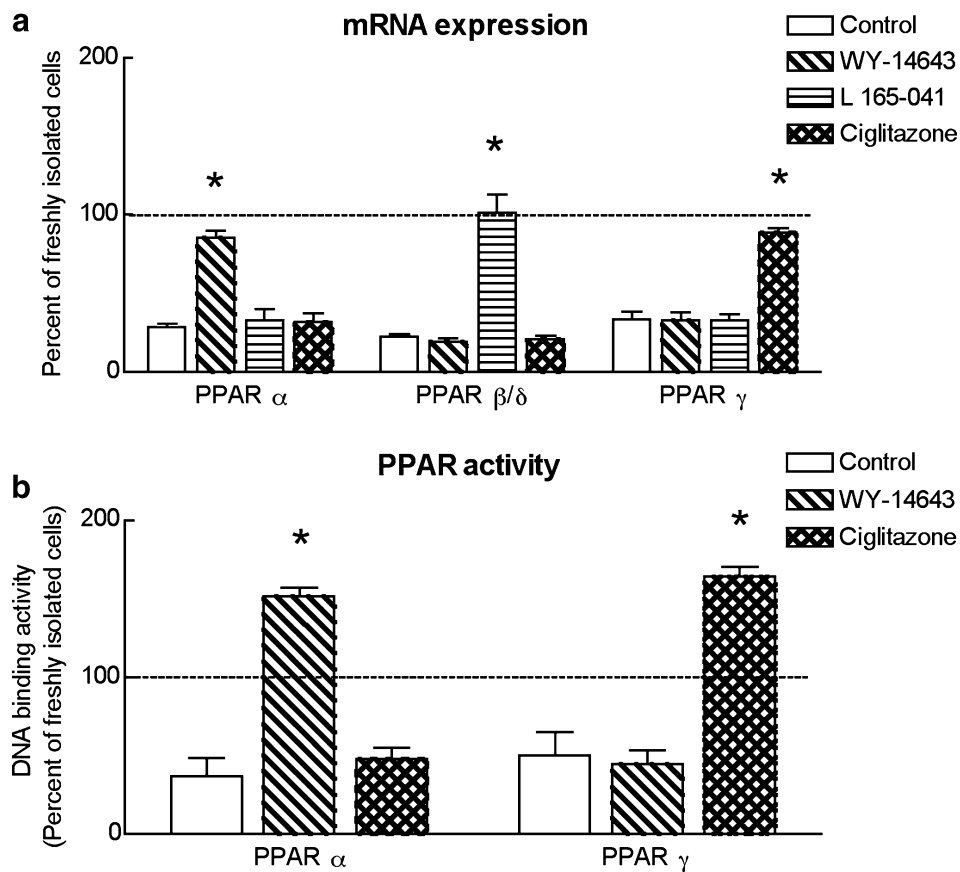


Fig. 5 Effect of specific activation of PPAR isoforms on mRNA expression (a) and DNA-binding activity (b) after 14 days of culture. a Activation of PPAR α by WY-14643 (100 nmol/l), of PPAR β/δ by L 165-041 (1 μ mol/l), and of PPAR γ by ciglitazone (10 nmol/l) restored

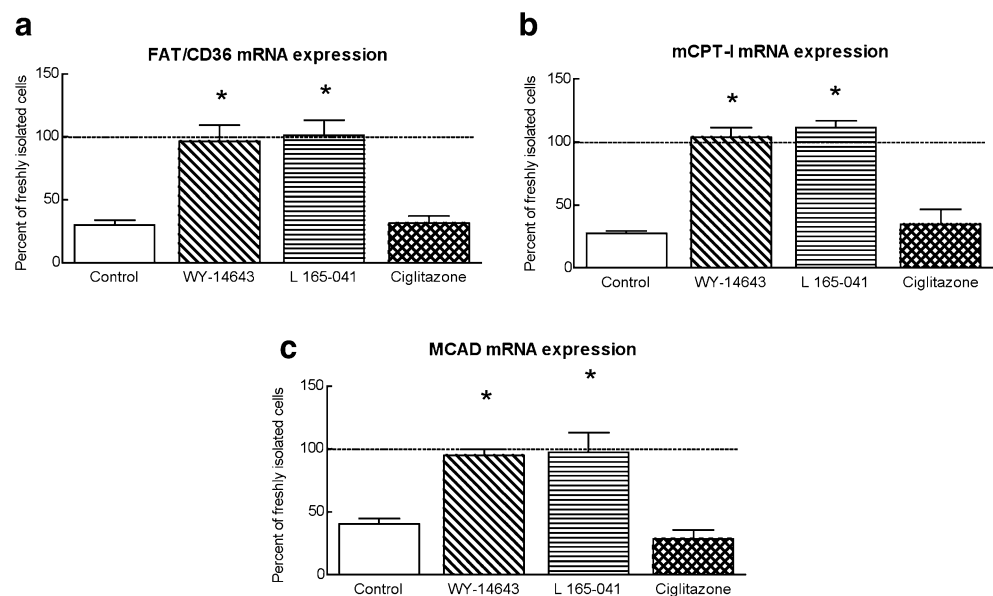
mRNA expression of the corresponding PPAR isoform. b DNA binding of PPAR α was increased by WY-14643 and that of PPAR γ by ciglitazone. Values are means \pm SEM of at least five determinations. * P <0.05 compared with untreated cells (control)

markers of hypertrophy, without influencing expression of genes of fatty acid metabolism.

Similar to previous observations by others in neonatal cardiac myocytes, we have found that all three isoforms,

PPAR α , PPAR β/δ , and PPAR γ , are expressed in adult rat cardiac myocytes. mRNA expression of each isoform rapidly decreased in ARC cultured in standard medium and remained low throughout the 14-day culture period. Conversely, protein

Fig. 6 Effect of activation of PPAR α , PPAR β/δ , and PPAR γ by WY-14643, L-165-041, and ciglitazone, respectively, on mRNA expression of FAT/CD36 (a), mCPT-I (b), and MCAD (c). Specific ligands of PPAR α and PPAR β/δ (WY-14643, L 165-041) restored expression of each regulatory protein of fatty acid oxidation. Activation of PPAR γ by ciglitazone had no effect. Values are means \pm SEM of at least four determinations. * P <0.05 compared with untreated cells (control)



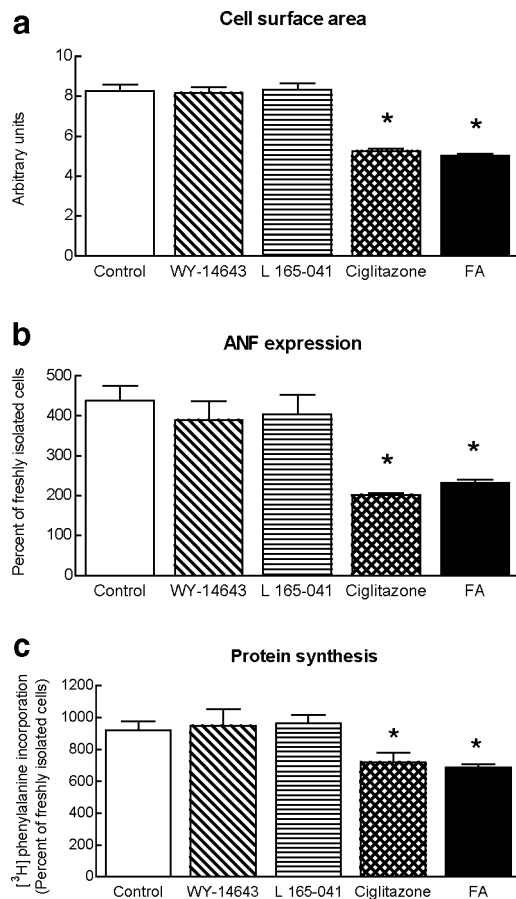


Fig. 7 Effect of activation of PPAR isoforms by specific ligands on cell surface (a), ANF mRNA expression (b), and de novo protein synthesis (c). Activation of PPAR α by WY-14643 and PPAR β/δ by L 165-041 had no effect. Activation of PPAR γ by ciglitazone decreased cell surface, ANF expression, and de novo protein synthesis to a comparable extent as fatty acid. Values are means \pm SEM of at least four determinations. * P <0.05 compared with untreated cells (control)

expression decreased only transiently and returned to levels measured immediately after isolation within 3 days, suggesting posttranscriptional compensation by as yet unknown mechanisms. However, DNA-binding activity of PPAR α and PPAR γ was reduced by roughly 50% during the entire culture period, compared with freshly isolated cells (binding activity of PPAR β/δ not measured). mRNA expression and DNA-binding activity exhibited a similar time-course most likely reflecting the fact that PPARs transactivate their own expression [3]. This is further supported by the observation that specific activation of PPAR α and PPAR γ by WY-14643 and ciglitazone, respectively, restored both DNA-binding activity and mRNA expression of the corresponding isoform. Although not measured, we anticipate that PPAR β/δ was also inactivated because mRNA expression was reduced and could be reactivated by L 165-041. Collectively, the results provide circumstantial evidence that transcriptional activity of all three PPAR isoforms is reduced in ARC undergoing phenotype transformation, despite unaltered protein expression.

There is evidence that PPAR signaling is altered during the development of maladaptive myocardial hypertrophy in vivo. Reduction of both myocardial expression and activity of PPAR α has been observed in rodents with mechanical overload induced by constriction of either the aorta [2, 48] or the pulmonary artery [38]. Mechanisms that may contribute to the inactivation of PPAR α during cardiac hypertrophy include phosphorylation of PPAR α by extracellular signal-regulated MAP kinase [2], increased expression of the competing repressor chicken ovalbumin upstream promoter-transcription factor (COUP-TF) [38], or reduced availability of the co-activator PGC-1 α [2, 20].

mRNA expression of FAT/CD36, CPT-I, and MCAD, which are target genes of PPAR α and PPAR β/δ , decreased in ARC concomitantly with the reduction of DNA-binding activity (and mRNA expression) of PPARs. An interesting finding was that both protein expression and palmitate oxidation were not reduced concomitantly but, similar to PPARs protein expression, was maintained at levels comparable to those measured in freshly isolated cardiac myocytes. A dissociation between mRNA and protein expression of genes of fatty acid oxidation has also been observed in hypertrophic myocardium of spontaneously hypertensive rats [39] and of mice with targeted overexpression of angiotensinogen in the myocardium [27]. In these rodent models of progressive hypertrophy, in vivo protein expression and enzyme activity of MCAD was maintained at control level during compensated hypertrophy, despite marked reduction of mRNA, but dropped markedly after the onset of heart failure [27, 39]. Taken together, these observations suggest the involvement of posttranscriptional mechanisms in the control of levels of regulatory proteins of fatty acid metabolism during cardiac myocyte remodeling. However, the underlying molecular events are presently not known.

Inclusion of fatty acids (oleate 0.25 mmol/l plus palmitate 0.25 mmol/l) in the culture medium restored mRNA expression of PPAR α , PPAR β/δ , and PPAR γ , and DNA-binding activity. Both mRNA and protein expression of FAT/CD36, mCPT-I, and MCAD increased to levels exceeding those measured in freshly isolated ARC. Concomitantly, fatty acid oxidation rate was higher than in freshly isolated cells. Analogous findings have been reported for neonatal rat cardiac myocytes [14, 45]. However, in contrast to observations in neonatal cardiac myocytes cultured for 48 h [45], exposure to fatty acid not only increased the expression of the fatty acid oxidation pathway, but also attenuated cardiac myocyte growth, protein synthesis, and expression of hypertrophy marker genes. After 14 days of culture, adult rat cardiac myocytes were smaller by 33%, and both ANF and BNP mRNAs were reduced by more than 50%. The results are compatible with the hypothesis that inactivation of PPAR signaling contributes to morphologic and metabolic remodeling of cardiac myocytes.

The contribution of individual PPAR isoforms to phenotypic modification of ARC has been determined in experiments using specific agonists. The results indicate that PPAR isoforms have distinct effects. Consistent with previous studies in neonatal cardiac myocytes in short-term culture [14], activation of PPAR α or PPAR β/δ by WY-14643 and L 165-041, respectively, restored expression of regulatory genes of fatty acid metabolism. Conversely, activation of PPAR γ by ciglitazone, as previously observed in neonatal cardiac myocytes [14], had no effect on metabolic genes.

In the present study, activation of PPAR α and PPAR β/δ had no effect on cardiac myocyte size, protein synthesis, and the expression of ANF and BNP. This is in apparent contrast to previous observations in neonatal cardiac myocytes. In fact, activation of PPAR α reduced the hypertrophic response in neonatal rat cardiac myocytes exposed to endothelin-1 [17, 21]. A similar effect has been observed after activation of PPAR β/δ by L 165-041 in phenylephrine-stimulated neonatal rat cardiac myocytes [30]. The reason for the absence of an antihypertrophic effect of activation of PPAR α and PPAR β/δ in ARC is not apparent from the available data. However, at least three major differences in the experimental conditions should be considered: First, ARC and neonatal cardiac myocytes exhibit differences in the signaling pathways involved in hypertrophy [42]. Second, in neonatal cardiac myocytes, antihypertrophic effects of PPAR activation have been studied during stimulation by endothelin-1 or phenylephrine [17, 21, 30]. Third, studies in neonatal cardiac myocytes were limited to 1 to 3 days [30, 43, 47], whereas in the present study ARC were followed for 14 days.

In contrast to activation of PPAR α and PPAR β/δ , activation of PPAR γ by ciglitazone markedly reduced cardiac myocyte growth and protein synthesis in ARC, and decreased mRNA expression of ANF and BNP. Antihypertrophic effects of PPAR γ signaling have also been observed in neonatal cardiac myocytes stimulated by angiotensin II [1, 47], phenylephrine [47], or mechanical strain [47]. Preliminary observations from our laboratory indicate that reactivation of PPAR γ also attenuates angiotensin-II-mediated hypertrophy of ARC [28]. Interestingly, mice with targeted knockout of PPAR γ in the myocardium develop ventricular hypertrophy even without exogenous hypertrophic stimulus, suggesting that PPAR γ may suppress the hypertrophic gene program even in unstressed conditions [10]. Moreover, the hypertrophic response to pressure overload is enhanced in mice with cardiac-myocyte-restricted PPAR γ deletion [10]. Conversely, PPAR γ agonists inhibit ventricular hypertrophy induced by aortic constriction in wild-type mice [1, 40].

Whereas upregulation of genes of fatty acid metabolism most likely is mediated by direct interaction of the PPAR/RXR heterodimer with the promoter region [4, 6], the molecular mechanisms of attenuation of the hypertrophic response is less clear. DNA-binding-independent inactivation

of other transcription factors (transrepression) may be involved in the antihypertrophic effects [7, 18, 29]. Studies in neonatal cardiac myocytes exposed to hypertrophic stimuli have demonstrated that activation of PPAR γ [43, 47], but also of PPAR α [43] and PPAR β/δ [30], inactivate NF- κ B that is essential for hypertrophy in this model [15, 31]. Observations in macrophages raise the possibility that PPAR γ may antagonize activity of other transcription factors potentially involved in hypertrophy, including activator protein-1 (AP-1) and STAT [33].

Collectively, this study demonstrates that PPAR activity considerably modulates phenotypic transformation of adult rat cardiac myocytes in culture. PPAR α and PPAR β/δ on one hand, and PPAR γ on the other hand, differ not only in their effects on the expression of regulatory proteins of fatty acid metabolism, but also in their modification of the hypertrophic response. This observation may be relevant for the development of therapeutic strategies designed to modify myocardial remodeling because restoration of fatty acid metabolism and attenuation of the hypertrophic response may differentially affect the remodeling process [24, 48].

Acknowledgment This work was supported by grants from the Swiss National Science Foundations (nos. 3200-067873 and 3100B0-109212/1) and the Swiss Heart Foundation.

References

- Asakawa M, Takano H, Nagai T, Uozumi H, Hasegawa H, Kubota N, Saito T, Masuda Y, Kadowaki T, Komuro I (2002) Peroxisome proliferator-activated receptor gamma plays a critical role in inhibition of cardiac hypertrophy in vitro and in vivo. *Circulation* 105:1240–1246
- Barger PM, Brandt JM, Leone TC, Weinheimer CJ, Kelly DP (2000) Deactivation of peroxisome proliferator-activated receptor-alpha during cardiac hypertrophic growth. *J Clin Invest* 105:1723–1730
- Blanquart C, Barbier O, Fruchart JC, Staels B, Glineur C (2003) Peroxisome proliferator-activated receptors: regulation of transcriptional activities and roles in inflammation. *J Steroid Biochem Mol Biol* 85:267–273
- Brandt JM, Djouadi F, Kelly DP (1998) Fatty acids activate transcription of the muscle carnitine palmitoyltransferase I gene in cardiac myocytes via the peroxisome proliferator-activated receptor alpha. *J Biol Chem* 273:23786–23792
- Cheng L, Ding G, Qin Q, Huang Y, Lewis W, He N, Evans RM, Schneider MD, Brako FA, Xiao Y, Chen YE, Yang Q (2004) Cardiomyocyte-restricted peroxisome proliferator-activated receptor-delta deletion perturbs myocardial fatty acid oxidation and leads to cardiomyopathy. *Nat Med* 10:1245–1250
- Cheng L, Ding G, Qin Q, Xiao Y, Woods D, Chen YE, Yang Q (2004) Peroxisome proliferator-activated receptor [delta] activates fatty acid oxidation in cultured neonatal and adult cardiomyocytes. *Biochem Biophys Res Commun* 313:277–286
- Daynes RA, Jones DC (2002) Emerging roles of PPARs in inflammation and immunity. *Nat Rev Immunol* 2:748–759
- de Vries JE, Vork MM, Roemen TH, de Jong YF, Cleutjens JP, van der Vusse GJ, van Bilsen M (1997) Saturated but not mono-

- unsaturated fatty acids induce apoptotic cell death in neonatal rat ventricular myocytes. *J Lipid Res* 38:1384–1394
9. Donath MY, Zapf J, Eppenberger-Eberhardt M, Froesch ER, Eppenberger HM (1994) Insulin-like growth factor I stimulates myofibril development and decreases smooth muscle alpha-actin of adult cardiomyocytes. *Proc Natl Acad Sci USA* 91:1686–1690
 10. Duan SZ, Ivashchenko CY, Russell MW, Milstone DS, Mortensen RM (2005) Cardiomyocyte-specific knockout and agonist of peroxisome proliferator-activated receptor- γ Both induce cardiac hypertrophy in mice. *Circ Res* 97:372–379
 11. Dyntaxa D, Eppenberger-Eberhardt M, Maedler K, Pruschy M, Eppenberger HM, Spinass GA, Donath MY (2001) Glucose and palmitic acid induce degeneration of myofibrils and modulate apoptosis in rat adult cardiomyocytes. *Diabetes* 50:2105–2113
 12. Eppenberger-Eberhardt M, Flamme I, Kurer V, Eppenberger HM (1990) Reexpression of alpha-smooth muscle actin isoform in cultured adult rat cardiomyocytes. *Dev Biol* 139:269–278
 13. Eppenberger-Eberhardt M, Messlerli M, Eppenberger HM, Reinecke M (1993) New occurrence of atrial natriuretic factor and storage in secretorally active granules in adult rat ventricular cardiomyocytes in long-term culture. *J Mol Cell Cardiol* 25:753–757
 14. Gilde AJ, van der Lee KA, Willemsen PH, Chinetti G, van der Leij FR, van der Vusse GJ, Staels B, van Bilsen M (2003) Peroxisome proliferator-activated receptor (PPAR) alpha and PPARbeta/delta, but not PPARgamma, modulate the expression of genes involved in cardiac lipid metabolism. *Circ Res* 92:518–524
 15. Higuchi Y, Otsu K, Nishida K, Hirotani S, Nakayama H, Yamaguchi O, Matsumura Y, Ueno H, Tada M, Hori M (2002) Involvement of reactive oxygen species-mediated NF-kappa B activation in TNF-alpha-induced cardiomyocyte hypertrophy. *J Mol Cell Cardiol* 34:233–240
 16. Huss JM, Kelly DP (2004) Nuclear receptor signaling and cardiac energetics. *Circ Res* 95:568–578
 17. Irukayama-Tomobe Y, Miyauchi T, Sakai S, Kasuya Y, Ogata T, Takanashi M, Iemitsu M, Sudo T, Goto K, Yamaguchi I (2004) Endothelin-1-induced cardiac hypertrophy is inhibited by activation of peroxisome proliferator-activated receptor-alpha partly via blockade of c-Jun NH2-terminal kinase pathway. *Circulation* 109:904–910
 18. Jones DC, Ding X, Zhang TY, Daynes RA (2003) Peroxisome proliferator-activated receptor alpha negatively regulates T-bet transcription through suppression of p38 mitogen-activated protein kinase activation. *J Immunol* 171:196–203
 19. Kanda H, Nohara R, Hasegawa K, Kishimoto C, Sasayama S (2000) A nuclear complex containing PPARalpha/RXRalpha is markedly downregulated in the hypertrophied rat left ventricular myocardium with normal systolic function. *Heart Vessels* 15:191–196
 20. Lehman JJ, Kelly DP (2002) Transcriptional activation of energy metabolic switches in the developing and hypertrophied heart. *Clin Exp Pharmacol Physiol* 29:339–345
 21. Liang F, Wang F, Zhang S, Gardner DG (2003) Peroxisome proliferator activated receptor (PPAR)alpha agonists inhibit hypertrophy of neonatal rat cardiac myocytes. *Endocrinology* 144:4187–4194
 22. Montessuit C, Papageorgiou I, Campos L, Lerch R (2006) Retinoic acids increase expression of GLUT4 in dedifferentiated and hypertrophied cardiac myocytes. *Basic Res Cardiol* 101:27–35
 23. Montessuit C, Rosenblatt-Velin N, Papageorgiou I, Campos L, Pellieux C, Palma T, Lerch R (2004) Regulation of glucose transporter expression in cardiac myocytes: p38 MAPK is a strong inducer of GLUT4. *Cardiovasc Res* 64:94–104
 24. Nemoto S, Razeghi P, Ishiyama M, De Freitas G, Taegtmeyer H, Carabello BA (2005) PPAR- γ agonist rosiglitazone ameliorates ventricular dysfunction in experimental chronic mitral regurgitation. *Am J Physiol Heart Circ Physiol* 288:H77–82
 25. Opie LH, Commerford PJ, Gersh BJ, Pfeffer MA (2006) Controversies in ventricular remodelling. *Lancet* 367:356–367
 26. Osorio JC, Stanley WC, Linke A, Castellari M, Diep QN, Panchal AR, Hintze TH, Lopaschuk GD, Recchia FA (2002) Impaired myocardial fatty acid oxidation and reduced protein expression of retinoid X receptor-alpha in pacing-induced heart failure. *Circulation* 106:606–612
 27. Pellieux C, Aasum E, Larsen TS, Montessuit C, Papageorgiou I, Pedrazzini T, Lerch R (2006) Overexpression of angiotensinogen in the myocardium induces downregulation of the fatty acid oxidation pathway. *J Mol Cell Cardiol* 41:459–466
 28. Pellieux C, Montessuit C, Papageorgiou I, Lerch R (2005) ROS mediate AngII-induced metabolic and morphologic phenotype adaptation through PPAR inactivation. *J Mol Cell Cardiol* 38:1056
 29. Planavila A, Laguna JC, Vazquez-Carrera M (2005) Nuclear factor-kappaB activation leads to down-regulation of fatty acid oxidation during cardiac hypertrophy. *J Biol Chem* 280:17464–17471
 30. Planavila A, Rodriguez-Calvo R, Jove M, Michalik L, Wahli W, Laguna JC, Vazquez-Carrera M (2005) Peroxisome proliferator-activated receptor beta/delta activation inhibits hypertrophy in neonatal rat cardiomyocytes. *Cardiovasc Res* 65:832–841
 31. Purcell NH, Tang G, Yu C, Mercurio F, DiDonato JA, Lin A (2001) Activation of NF-kappa B is required for hypertrophic growth of primary rat neonatal ventricular cardiomyocytes. *Proc Natl Acad Sci USA* 98:6668–6673
 32. Remondino A, Rosenblatt-Velin N, Montessuit C, Tardy I, Papageorgiou I, Dorsaz PA, Jorge-Costa M, Lerch R (2000) Altered expression of proteins of metabolic regulation during remodeling of the left ventricle after myocardial infarction. *J Mol Cell Cardiol* 32:2025–2034
 33. Ricote M, Li AC, Willson TM, Kelly CJ, Glass CK (1998) The peroxisome proliferator-activated receptor-gamma is a negative regulator of macrophage activation. *Nature* 391:79–82
 34. Ritchie RH, Rosenkranz AC, Huynh LP, Stephenson T, Kaye DM, Dusting GJ (2004) Activation of IP prostanoid receptors prevents cardiomyocyte hypertrophy via cAMP-dependent signaling. *Am J Physiol Heart Circ Physiol* 287:H1179–1185
 35. Rosenblatt-Velin N, Lerch R, Papageorgiou I, Montessuit C (2004) Insulin resistance in adult cardiomyocytes undergoing dedifferentiation: role of GLUT4 expression and translocation. *FASEB J* 18:872–874
 36. Rosenblatt-Velin N, Montessuit C, Papageorgiou I, Terrand J, Lerch R (2001) Postinfarction heart failure in rats is associated with upregulation of GLUT-1 and downregulation of genes of fatty acid metabolism. *Cardiovasc Res* 52:407–416
 37. Rosenblatt-Velin N, Montessuit C, Papageorgiou I, Lerch R (2002) Fatty acids modulated gene expression in adult rat cardiomyocytes in culture. *J Mol Cell Cardiol* 34:A55
 38. Sack MN, Disch DL, Rockman HA, Kelly DP (1997) A role for Sp and nuclear receptor transcription factors in a cardiac hypertrophic growth program. *Proc Natl Acad Sci USA* 94:6438–6443
 39. Sack MN, Rader TA, Park S, Bastin J, McCune SA, Kelly DP (1996) Fatty acid oxidation enzyme gene expression is down-regulated in the failing heart. *Circulation* 94:2837–2842
 40. Sakai S, Miyauchi T, Irukayama-Tomobe Y, Ogata T, Goto K, Yamaguchi I (2002) Peroxisome proliferator-activated receptor-gamma activators inhibit endothelin-1-related cardiac hypertrophy in rats. *Clin Sci (Lond)* 103(Suppl 48):16S–20S
 41. Schaub MC, Hefti MA, Harder BA, Eppenberger HM (1997) Various hypertrophic stimuli induce distinct phenotypes in cardiomyocytes. *J Mol Med* 75:901–920
 42. Schluter KD, Millar BC, McDermott BJ, Piper HM (1995) Regulation of protein synthesis and degradation in adult ventricular cardiomyocytes. *Am J Physiol Cell Physiol* 269:C1347–1355
 43. Takano H, Nagai T, Asakawa M, Toyozaki T, Oka T, Komuro I, Saito T, Masuda Y (2000) Peroxisome proliferator-activated

- receptor activators inhibit lipopolysaccharide-induced tumor necrosis factor- α expression in neonatal rat cardiac myocytes. *Circ Res* 87:596–602
44. van Bilsen M, Smeets PJ, Gilde AJ, van der Vusse GJ (2004) Metabolic remodelling of the failing heart: the cardiac burn-out syndrome? *Cardiovasc Res* 61:218–226
45. van der Lee KA, Vork MM, De Vries JE, Willemsen PH, Glatz JF, Reneman RS, Van der Vusse GJ, Van Bilsen M (2000) Long-chain fatty acid-induced changes in gene expression in neonatal cardiac myocytes. *J Lipid Res* 41:41–47
46. Watanabe K, Fujii H, Takahashi T, Kodama M, Aizawa Y, Ohta Y, Ono T, Hasegawa G, Naito M, Nakajima T, Kamijo Y, Gonzalez FJ, Aoyama T (2000) Constitutive regulation of cardiac fatty acid metabolism through peroxisome proliferator-activated receptor alpha associated with age-dependent cardiac toxicity. *J Biol Chem* 275:22293–22299
47. Yamamoto K, Ohki R, Lee RT, Ikeda U, Shimada K (2001) Peroxisome proliferator-activated receptor gamma activators inhibit cardiac hypertrophy in cardiac myocytes. *Circulation* 104:1670–1675
48. Young ME, Laws FA, Goodwin GW, Taegtmeyer H (2001) Reactivation of peroxisome proliferator-activated receptor alpha is associated with contractile dysfunction in hypertrophied rat heart. *J Biol Chem* 276:44390–44395