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Potential Relevance of α₁-Adrenergic Receptor Autoantibodies in Refractory Hypertension

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Abstract

Background: Agonistic autoantibodies directed at the α₁-adrenergic receptor (α₁-AAB) have been described in patients with hypertension. We implied earlier that α₁-AAB might have a mechanistic role and could represent a therapeutic target.

Methodology/Principal Findings: To pursue the issue, we performed clinical and basic studies. We observed that 41 of 81 patients with refractory hypertension had α₁-AAB; after immunoadsorption blood pressure was significantly reduced in these patients. Rabbits were immunized to generate α₁-adrenergic receptor antibodies (α₁-AB). Patient α₁-AAB and rabbit α₁-AB were purified using affinity chromatography and characterized both by epitope mapping and surface plasmon resonance measurements. Neonatal rat cardiomyocytes, rat vascular smooth muscle cells (VSMC), and Chinese hamster ovary cells transfected with the human α₁A-adrenergic receptor were incubated with patient α₁-AAB and rabbit α₁-AB and the activation of signal transduction pathways was investigated by Western blot, confocal laser scanning microscopy, and gene expression. We found that phospholipase A2 group IIA (PLA2-IIA) and L-type calcium channel (Cacna1c) genes were upregulated in cardiomyocytes and VSMC after stimulation with both purified antibodies. We showed that patient α₁-AAB and rabbit α₁-AB result in protein kinase C alpha activation and transient extracellular-related kinase (EKR1/2) phosphorylation. Finally, we showed that the antibodies exert acute effects on intracellular Ca^{2+} in cardiomyocytes and induce mesentery artery segment contraction.

Conclusions/Significance: Patient α₁-AAB and rabbit α₁-AB can induce signaling pathways important for hypertension and cardiac remodeling. Our data provide evidence for a potential clinical relevance for α₁-AAB in hypertensive patients, and the notion of immunity as a possible cause of hypertension.

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Introduction

Autoimmunity with agonistic autoantibodies directed at endogenous receptors can cause Graves' disease through the thyrotropin receptor and promotes insulin release via CD38 [1,2]. Agonistic antibodies that stimulate the angiotensin (Ang) II AT1 receptor have been described in preeclampsia and humorally mediated kidney transplant rejection [3,4]. The most compelling case for agonistic autoantibody-mediated disease has been that of β₁-adrenergic receptor autoantibodies observed in patients with dilated cardiomyopathy and in a rat model fulfilling Koch's postulates [5]. However, autoantibodies could also merely be an epiphenomenon in many instances; convincing data are still pending.

α₁-adrenergic receptor (α₁-AR) signaling mediates several cardiovascular actions such as vascular smooth muscle cell

(VSMC) contraction, cardiac inotropy, hypertrophy, and remodeling [6]. α₁-AR are predominantly located postsynaptically on VSMC, where they are the targets of circulating norepinephrine and regulate VSMC contraction [7]. Sympathetic over-activity in hypertension and accompanying excess stimulation of postsynaptic α₁-AR supports the use of selective α₁-AR inhibitors as antihypertensive drugs. However, α₁-AR blockade was discontinued in the Antihypertensive and Lipid-Lowering Treatment to Prevent Heart Attack Trial (ALLHAT) because of a putative increased risk for heart failure [8], a highly controversial decision that has been sharply criticized [9]. The Valsartan Heart Failure Trial 2 (Val-HeFT2) showed that α₁-AR blockade was beneficial in heart failure. α₁-AR can contribute to cardiomyocyte hypertrophy. Huang et al demonstrated a protective effect of the α₁A-AR-subtype in cardiac myocytes and defined an extracellular-

regulated kinase (ERK) signaling pathway that is required for myocyte survival [10]. Hearts of α_1-AR gene-deleted mice had increased interstitial fibrosis, increased apoptosis, and failed induction of the fetal hypertrophic gene program after pressure overload, indicating that α_{1A}-AR are required for myocardial adaptation to stress [11,12].

Others and we have described agonistic autoantibodies (α_1-AAB) against the α_1-AR [13,14,15]. Earlier, we examined immunoglobulin fractions in 54 severely hypertensive patients and found α_1-AAB in 44% [15]. However, 12% of normotensive control subjects also harbored α_1-AAB. Zhou et al. immunized rats with a peptide from the α_1-AR epitope [16]. The rats developed α_1-AR antibodies (α_1-AB) and cardiac hypertrophy. However, the link between α_1-AB formation and cardiac remodeling remains unclear. We have now performed additional studies to elucidate the pathophysiological relevance of α_1-AAB. We show that removal of α_1-AAB with immunoadsorption is feasible and lowers blood pressure. We raised α_1-AB in rabbit and purified the α_1-AB from rabbits and α_1-AAB from patients by affinity chromatography. After confirming binding and functional specificity of the isolated rabbit α_1-AB and human α_1-AAB, we performed gene expression analysis in cardiomyocytes and vascular smooth muscle cells (VSMC). We show that both rabbit α_1-AB and human α_1-AAB can evoke calcium signaling and contract vessel preparations via protein kinase C alpha (PKC-α) activation and transient extracellular-related kinase (ERK 1/2) phosphorylation. Our data suggest that human α_1-AAB can induce signaling pathways involved in hypertension and cardiac remodeling, suggesting a potential clinical relevance of α_1-AAB.

Results

We analyzed α_1-AAB in 81 patients with refractory hypertension, who required ≥ 3 antihypertensive medications. Severe hypertension-induced target organ damage was present in every patient, including funduscopic changes, cardiac abnormalities, and kidney damage. Fourty-one patients (51%) featured α_1-AAB as assessed by cardiomyocyte contraction assay. Microalbuminuria was detected in 33%, diastolic dysfunction in 87%, left ventricular (LV) hypertrophy in 85%, and reduced ejection fraction in 13% of α_1-AAB positive patients. The patient characteristics are outlined in Table 1.

Table 1. Clinical features of the patients classified as α_1-AR-AA positive or negative.

α_1-AAB	Positive	Negative
Number	41	40
Age range	46–81 years	42–81 years
Male	59%	60%
Female	41%	40%
Medication classes	4.3	4.7
Goal blood pressure	77%	76%
Heart failure	64%	57%
Reduced ejection fraction	13%	24%
Diastolic dysfunction	87%	81%
Left ventricular hypertrophy	85%	76%
Microalbuminuria	33%	36%

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Figure 1 shows data from the five α_1-AAB positive patients undergoing immunoadsorption. The treatments were performed daily for 5 days. The cardiomyocyte contraction assay documented gradually decreasing α_1-AAB activity during the course of the five immunoadsorptions (Figure 1A, B). At the end of five days, the activity was in the normal range. The decreased α_1-AAB activity persisted for the 180 day observation period (Figure 1C). Blood pressure recordings performed before and after 5 days of treatment showed a significant reduction in mean arterial pressure (MAP), compared to initial values that remained significantly reduced for the observation period of 180 days (Figure 1D).

α_1-AAB were directed against the first extracellular loop (eL1) in 24% and against the second extracellular loop (eL2) in 27% of the hypertensive patients (Figure 2A). Epitope mapping for the first and second extracellular loop of the α_{1A}-AR by cardiac contraction assay is shown in Figure 2B and C. Overlapping peptide sequences were tested for competition in cardiac contraction assay. For extracellular loop 1 (eL1) the peptide sequence P1 (YWAFGR) diminished the spontaneous beating rate response completely. The peptide sequence P2 (APEDET) competed for the antibody extracellular loop 2 (eL2) effect. Since activating autoantibodies against the second loop have already been described for the AT1-R and β_1-AR receptor, we analyzed α_1-AAB against the second extracellular loop of α_{1A}-AR in this study.

We purified α_1-AAB from patients by affinity chromatography using the peptide of the second extracellular loop of the α_{1A}-AR. We then used surface plasmon resonance (SPR) measurements to determine the binding affinity and specificity of purified autoantibody fractions. Sensorgrams, depicted in Figure 3, demonstrate that the antibodies displayed a high binding affinity (Kd$\sim$50 nM) to the biotinylated peptide corresponding to eL2 of the α_1-AR immobilized to the SA-sensorchip. This affinity-purified antibody fraction also showed weak cross-reactivity with the biotinylated peptide corresponding to the eL1 of the α_1-AR (Figure 3A). However, this binding was negligible compared to the strong eL2 interaction.

We next raised a peptide antibody against the second extracellular loop of the α_1-AR (rabbit α_1-AB) and purified the antibody on the same peptide-containing affinity matrix. In SPR experiments, the rabbit α_1-AB produced regular association and dissociation kinetics reaching a signal of $\sim$2500 RU at a concentration of 80 µg/ml (Figure 3B). Purified α_1-AAB from patients and rabbit α_1-AB increased the beating rate of rat cardiomyocytes. This effect was dose-dependent (Figure 3C and D). The maximal response was obtained at an antibody dilution of 1:200 (0.5 and 0.6 µg/ml medium, respectively). The positive chronotropic effect was blocked by the α_1-AR antagonist prazosin (1 µM).

To elucidate the molecular pathways induced by α_1-AAB, we performed gene expression studies. We used Affymetrix microarrays for quantification of mRNA expression in cardiomyocytes and VSMC after treatment with purified α_1-AAB isolated from three different patients, rabbit α_1-AB, human control IgG, and the α_1-AR agonist phenylephrine (PE) for 24 h. We identified two genes with increased expression in the Affymetrix array that we then verified by TaqMan RT-PCR. These genes were *PLA2-IIA* and *Cacna1c*, as shown in Table 2. The upregulation of both genes was inhibited by the α_1-AR antagonist prazosin while no changes in gene expression were observed after the treatment with the control IgG.

We tested whether or not α_1-AAB from patients and rabbit α_1-AB could elicit Ca^{2+} signals. Figure 4A shows the reaction of neonatal cardiomyocytes intracellular Ca^{2+} transients in response to the addition of the purified patient α_1-AAB. There was a fast increase in the 340 nm/380 nm ratio, which peaked at less than 60 seconds and declined within 2 minutes to a plateau value
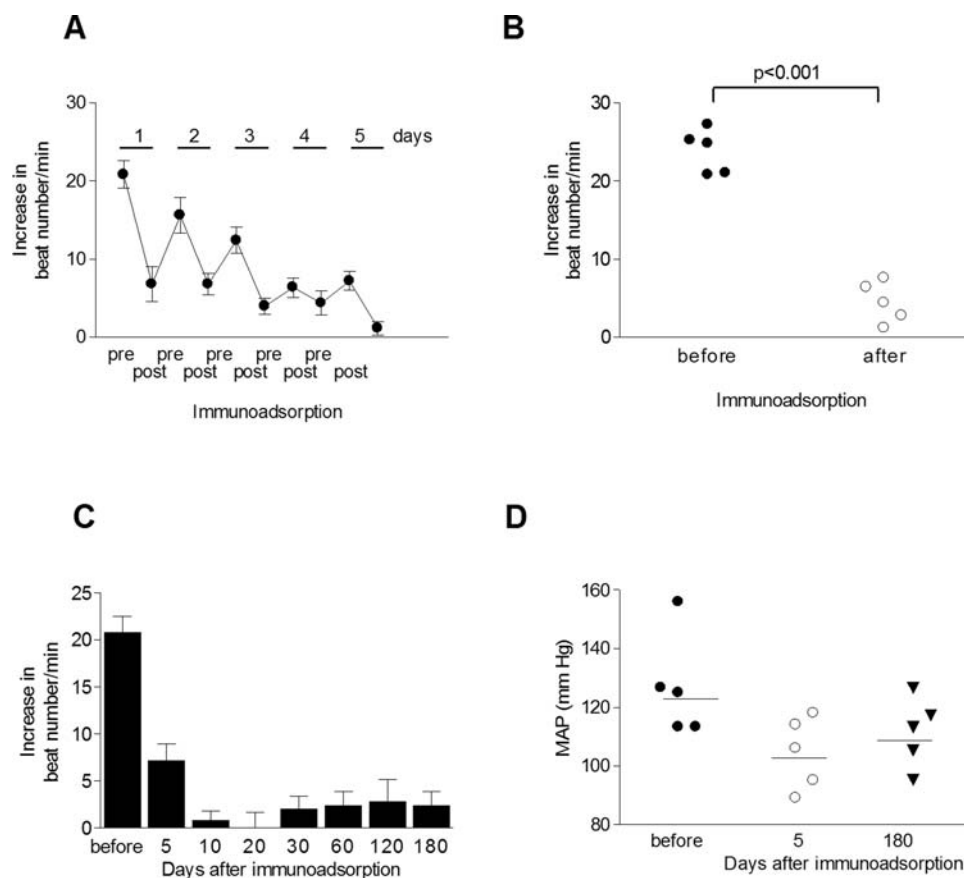
Figure 1. Effects of immunoadsorption on α₁-AAB and blood pressure. (**A**) Ordinate shows neonatal cardiomyocyte spontaneous beating rate; abscissa shows response to immunoadorption performed on a representative patient. The α₁-AAB activity decreased with every immunoadsorption with a total decrease in response over time. (**B**) Figure shows the initial spontaneous beating rate (closed circles). After five immunoadsorptions, this response is reduced to basal values (open circles) in all 5 patients. (**C**) Mean response of a representative patient in cardiomyocyte contraction assay over time to immunoadsorption is shown. (**D**) Mean arterial pressure (MAP) was measured 5 and 180 days after immunoadsorption. MAP was significantly reduced compared to before immunoadsorption.
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slightly above the control level before the addition of the α₁-AAB. Thus, α₁-AAB potently induced a rise in intracellular Ca^{2+} in the targeted neonatal cardiomyocytes. To elucidate whether or not this Ca^{2+} response could be common to an autoantibody-α₁-AR loop 2-type interaction, we used a rabbit α₁-AB. As shown in Figure 4B, this rabbit α₁-AB also generated an acute positive Ca^{2+} response in the cardiomyocytes with a similar time course as did

the human antibody preparation. These responses were not elicited by a control IgG. As illustrated in Figure 4C, an IgG prepared from an α₁-AAB negative patient was not able to raise the intracellular Ca^{2+}.

These results prompted myographic experiments in mesenteric arteries displayed in Figure 5. Treatment with KCl documented brisk viability of the preparation. PE and the rabbit α₁-AB both
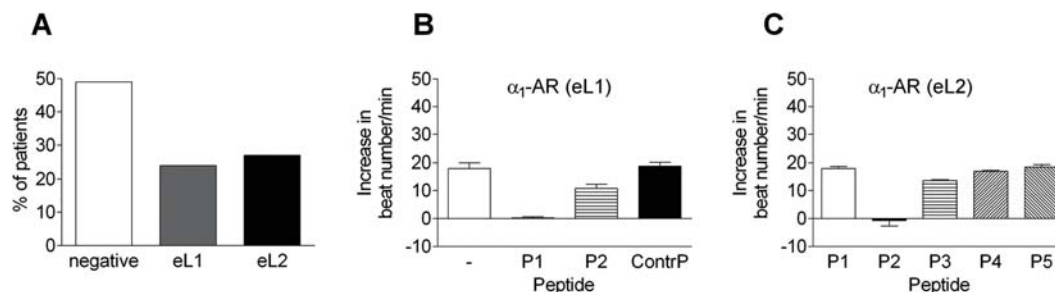

Figure 2. Epitope mapping for extracellular loop 1 and loop 2 of α₁A-AR is given. (**A**) α₁-AAB were directed against the first extracellular loop (eL1) in 24% and against the second extracellular loop (eL2) in 27% of the hypertensive patients. (**B**) The peptide sequence P1 (YWAFGR) and P2 (GRVFCNI) (partially) for eL1 were able to diminish the spontaneous beating rate response completely. (**C**) Epitope mapping for loop 2 is given for the following amino acid sequences: P1: GWRQPA, P2: APEDET, P3: TICQIN, P4: INEEPG, P5: GYVLFS. The sequence P2 (APEDET) was able to diminish the spontaneous beating rate response completely.
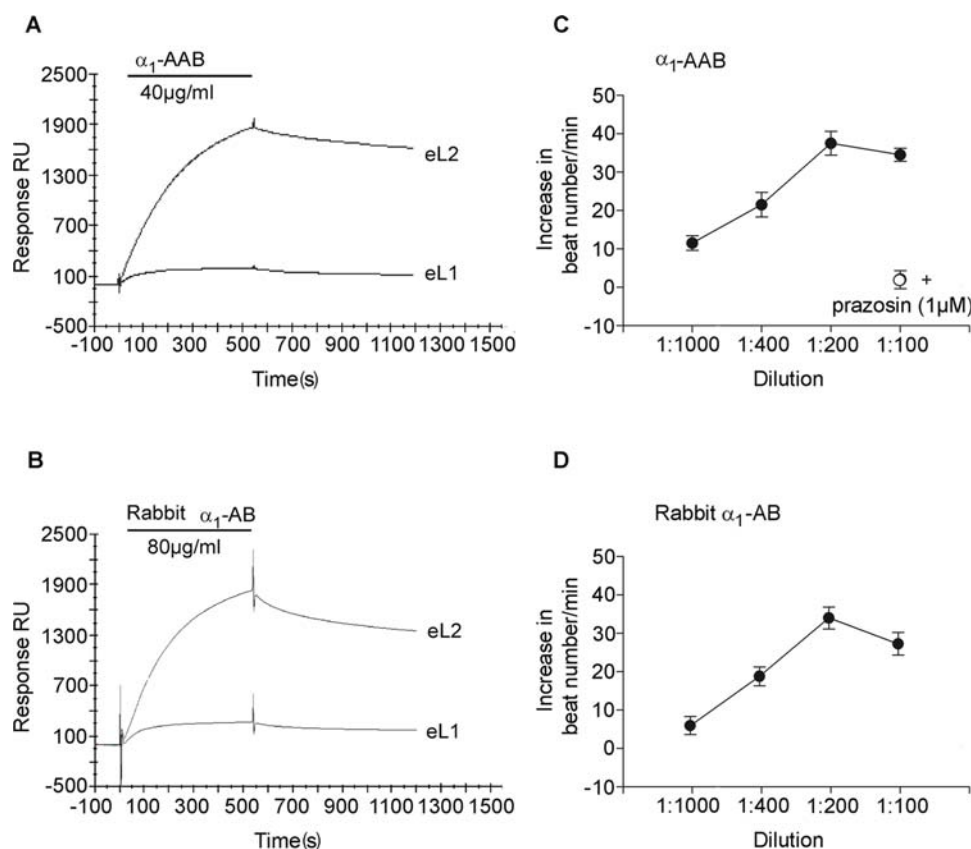doi:10.1371/journal.pone.0003742.g002

Figure 3. Binding and agonistic activity of patient α₁-AAB and rabbit α₁-AB. Surface plasmon resonance sensorgrams depicting antibody binding to α₁-AR peptides (**A** and **B**). Biotinylated peptide corresponding to the α₁ₐ-AR extracellular loop2 (eL2) were immobilized. A corresponding peptide to extracellular loop1 (eL1) served as negative control. α₁-AAB from a patient with refractory hypertension (**A**) and rabbit α₁-AB (**B**) bind exclusively to eL2. Note that the characteristics of the human antibody (**A**) and rabbit antibody (**B**) were the same. (**C**) Functional effects (cardiomyocyte contraction assay) of affinity-purified α₁-AAB (0.1–1 µg/ml medium) against second extracellular loop from a patient with refractory hypertension and (**D**) rabbit α₁-AB (0.12–1.2 µg/ml medium) against second extracellular loop. The functional findings corroborate the BIAcor results.
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were able to constrict the vessel (Figure 5A). The effect of α₁-AAB from two patients and from rabbit α₁-AB was compared to half-maximal and maximal effective PE dosages, producing 50% and 100% of vessel constriction. Patient α₁-AAB and rabbit α₁-AB showed marked vasoconstriction activity. Control IgG from human and rabbits had no effect (Figure 5B).

We then examined signal transduction. We concentrated on PKC-α and ERK 1/2 as both have been shown to be important in

Table 2. Differential expression of *PLA2-IIA* and *Cacna1c* in cardiomyocytes and VSMC after treatment with patient α₁-AAB, rabbit rabbit α₁-AB or PE (Fold changes in TaqMan analysis).

	α₁-AAB	rabbit α₁-AB	PE
PLA2-IIA			
Cardiomyocytes	2.3	6.2	4.0
VSMC	4.8	2.5	5.1
Cacna1c			
Cardiomyocytes	2.2	1.7	4.0
VSMC	2.0	1.8	2.2

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α₁-AR-stimulated hypertension-induced target organ damage [6]. As shown in Figure 6, we found that α₁-AAB and rabbit α₁-AB exposure to cardiomyocytes or VSMC resulted in PKC-α activation, as did the positive PE control. These effects were blocked completely by the specific PKC-α blocker, Gö 6976. Additionally, the incubation of Chinese hamster ovary (CHO) cells stably transfected with human α₁ₐ-AR (CHO/α₁ₐ-AR) with α₁-AAB resulted in PKC-α activation, which was blocked by the peptide P2, corresponding to the binding site of the α₁-AAB (Figure 7A).

We then studied ERK 1/2 phosphorylation and the upstream phosphatidylinositol 3 (PI3)-kinase activity in CHO/α₁ₐ-AR cells. Incubation with human α₁-AAB resulted in ERK 1/2 phosphorylation. The PI3-kinase inhibitor, LY294002, inhibited the ERK 1/2 phosphorylation (Figure 7B). Additional hypertensive patients, who were either α₁-AAB positive or negative in cardiomyocyte contraction assay, were characterized by ERK 1/2 activation with immunoblotting (Figure 8). α₁-AAB from three patients induce a transient ERK 1/2 phosphorylation similar to that evoked by PE and rabbit α₁-AB in neonatal cardiomyocytes. Phosphorylation was blocked by prazosin (Figure 8A). A similar activation was obtained in CHO/α₁ₐ-AR cells. The activation was specifically blocked by peptide P2 (Figure 8B). Fractions eluted from patients, who were negative in the cardiomyocyte contraction assay, failed to activate ERK 1/2.
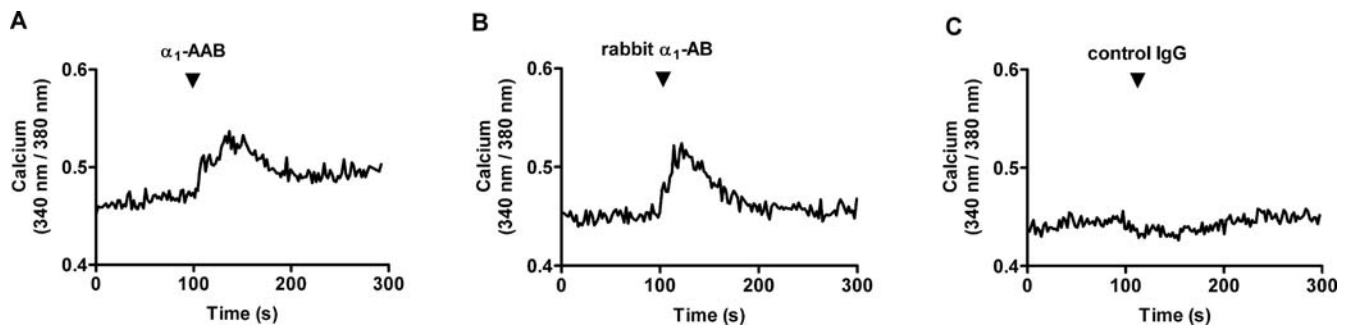
Figure 4. Representative traces of responses in intracellular Ca^{2+} of cultivated neonatal rat cardiomyocytes exposed to isolated patient α$_1$-AAB and rabbit α$_1$-AB are shown. (A) α$_1$-AAB isolated from the serum of a patient with refractory hypertension elicited a Ca^{2+} signal. (B) The rabbit α$_1$-AB gave a similar Ca^{2+} signal. (C) A human control IgG preparation was unable to affect intracellular Ca^{2+}. Cardiomyocytes were electrically stimulated at 1 Hz, and the peak Ca^{2+} was monitored.
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Discussion

The important findings in this study are that isolated α$_1$-AAB und generated α$_1$-AB show similar binding characteristics by surface plasmon resonance sensorgram and functional testing. The antibodies induce a Ca^{2+} dependent signal transduction cascade in VSMC and cardiomyocytes that are both important to the pathophysiology of hypertension and cardiac remodeling. By gene array studies, we showed that the isolated patient α$_1$-AAB and rabbit α$_1$-AB both upregulate two gene types, namely *PLA2-IIA* and *Cacna1c*. In a proof-of-concept, non-controlled trial, we show that removal of α$_1$-AAB by immunoadsorption lowers blood pressure in α$_1$-AAB positive patients with intractable primary hypertension.

The entire idea of "agonistic" autoantibodies contributing to cardiovascular disease is controversial [17]. Antibodies directed at receptors can block or stimulate their targets. Hallmark example of the latter action is Graves' disease where antibodies directed at the thyroid stimulating hormone receptor exert an agonistic action. Recently, compelling evidence has been presented regarding agonistic antibodies directed against the α$_1$-AR, the β-ARs, the Ang II AT1-R, and the platelet-derived growth factor-alpha receptor, as reviewed elsewhere [17]. The antibodies could play a

pathogenic role in various cardiovascular diseases, including hypertension, cardiomyopathy, preeclampsia, acute humoral rejection, and connective tissue disease.

Earlier, we speculated that α$_1$-AAB could contribute to hypertension [15]. Our goal here was to give the notion of α$_1$-AAB a more robust scientific basis. Thus, we verified our candidate by generating α$_1$-AB by immunization. Concomitantly, we subjected patients from our collective who harbored α$_1$-AAB to immunoadsorption. We found in our uncontrolled trial that lowering α$_1$-AAB titers was associated with a lower blood pressure. We did not perform a randomized double blind, crossover trial. Nonetheless, our study meets class I (safety) criteria and suggests that a future class II (efficacy) trial might be warranted. We cannot exclude the possibility that short-term effects of the immunoadsorption, such as circulating blood volume changes during apheresis or other confounders contributed to the reduction in blood pressure. Since the reduction in blood pressure persisted for the observation period of 180 days, we believe that removal of α$_1$-AAB by apheresis was the main cause for the blood pressure reduction. Within the five days immunoadsorption period, the level of α$_1$-AAB decreased gradually. Thereafter, α$_1$-AAB could not be detected after successful immuoadsorption in these patients for the entire observation period
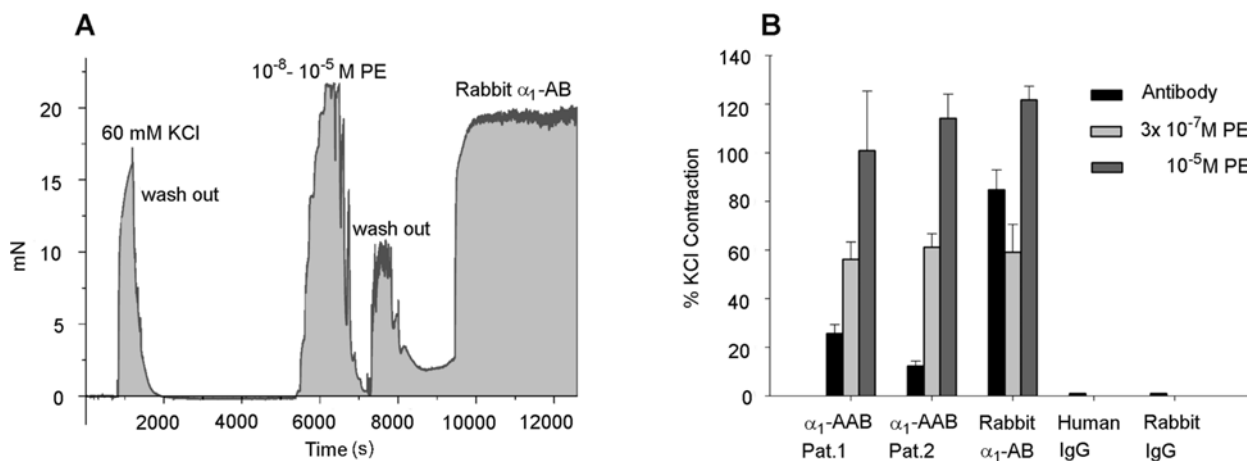

Figure 5. Contractile effect of patient α$_1$-AAB and rabbit α$_1$-AB in mesenteric arteries is given. A brisk KCl response is documented. (A) Representative experiment showing the contractile response to phenylephrine (PE, 10 nM–10 µM) and rabbit α$_1$-AB (50 µg in 5 ml PBS buffer). The PE and antibody responses were similar in kind. (B) Contractile response of human α$_1$-AAB isolated from two patients (5 µg in 5 ml PBS buffer) and rabbit α$_1$-AB (50 µg in 5 ml PBS buffer) are compared to the PE response (300 nM and 10 µM, respectively) is shown. Contractions are expressed as % KCl response from patient 1 and patient 2. The human antibody responses were less than the low and high-dose PE responses. The rabbit α$_1$-AB responses approached the PE responses. Two columns on the right are control human and control rabbit IgG showing no response.
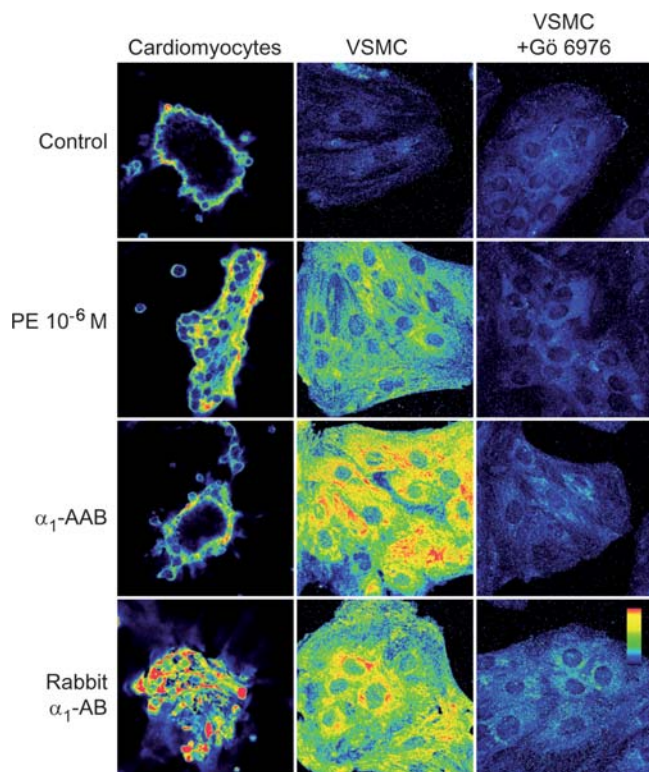doi:10.1371/journal.pone.0003742.g005

Figure 6. Protein kinase C alpha (PKC-α) activation in cardiomyocytes and vascular smooth muscle cells (VSMC) after 2 min incubation with PE, α₁-AAB from patients, and rabbit α₁-AB is demonstrated. Horizontal rows show regimens, namely, untreated control, PE, patient α₁-AAB, and rabbit α₁-AB. Vertical columns show cardiomyocyte and VSMC responses. Yellow shows PKC-α activation; red is more intense activation. Gö 6976 is a PKC-α inhibitor, which blocked all responses.
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of 180 days. A similar state-of-affairs has been described for β₁-AAB in dilated cardiomyopathy after immunoadsorption. These data suggest that immunomodulation by removal or neutralization of the AAB might represent a potential therapeutic strategy [18].

We isolated the detected α₁-AAB and the α₁-AB that we generated against the same epitope in rabbits, using the same affinity purification protocol. Since we used the same peptide sequence for epitope mapping in the cardiomyocyte contraction assay, immunization in the rabbit, and isolation in the affinity column, we are confident that we isolated solely α₁-AB. Before using this material to learn more about α₁-AR signaling in VSMC and cardiomyocytes, we confirmed binding specificity by functional (cardiac contraction assay and ERK 1/2 phosphorylation) and biochemical (surface plasmon resonance measurement) verification methods. We then performed an Affymetrix gene expression study. We followed up on the results to pursue two candidate genes, *PLA2-IIA* and *Cacna1c* that were upregulated in the display, as verified by RT-PCR. Both genes contribute to signaling pathways in hypertension and atherosclerosis. Phospholipases A2 are acute-phase reactants and play an important role in digestion and metabolism of phospholipids, as well as in production of precursors for inflammatory reactions. Plasma PLA2-IIA levels are increased in systemic inflammation, including, rheumatoid arthritis and cardiovascular diseases [19,20,21]. In infarcted hearts, expression of PLA2-IIA was markedly increased in damaged cardiomyocytes [22]. Inhibition of PLA2-IIA also prevented cardiac fibrosis in spontaneously hypertensive rats [23].

Another important finding accrued is the fact that both the α₁-AAB from patients and the rabbit α₁-AB affected intracellular Ca²⁺ at two different levels, namely the acute, short-term elevation of intracellular Ca²⁺, and the increased transcript expression of the voltage-gated L-type Ca²⁺ channel pore subunit. Acute administration of the purified antibodies to neonatal cardiomyocytes produced a typically shaped Ca²⁺ transient. The onset of the cytosolic Ca²⁺ response occurred within few seconds reaching its maximum at less than one minute. α₁-AR stimulation potentiates L-type Ca²⁺ current through CaMK II activation in rat ventricular myocytes [24].
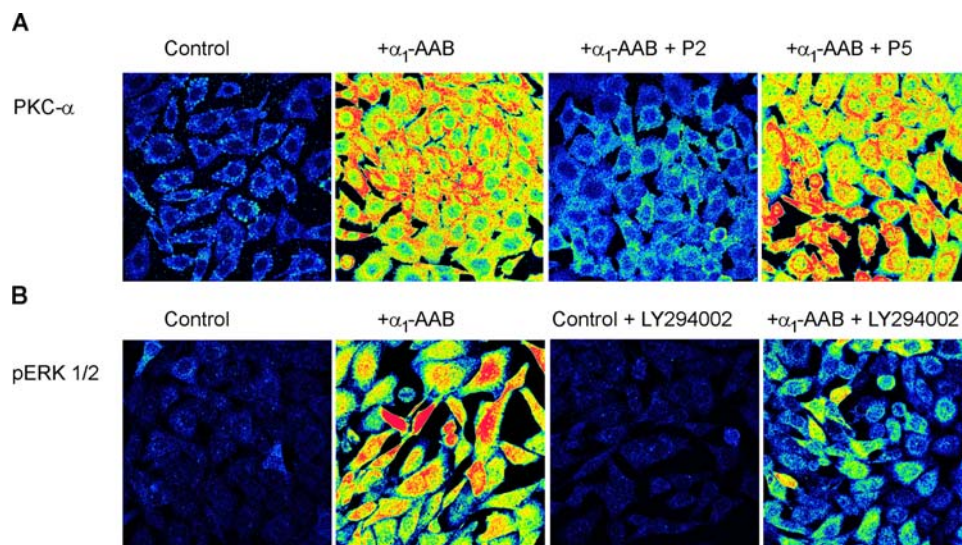

Figure 7. PKC-α and ERK 1/2 activation in CHO cells stably transfected with human α₁A-AR (CHO/α₁A-AR) by α₁-AAB is demonstrated. (**A**) Incubation of CHO/α₁A-AR cells with α₁-AAB for 2 min resulted in a PKC-α activation, which was blocked by the peptide P2, but not by the peptide P5. (**B**) ERK 1/2 phosphorylation after incubation with α₁-AAB for 5 min is shown. Inhibition of the upstream phosphatidylinositol 3 (PI3)-kinase activity by the inhibitor LY294002 strongly reduced ERK 1/2 phosphorylation. Yellow shows PKC-α and ERK 1/2 activation, respectively; red is more intense activation.
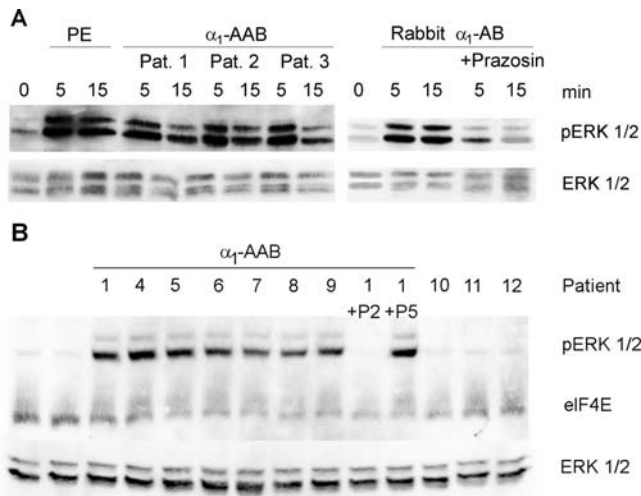doi:10.1371/journal.pone.0003742.g007

Figure 8. Activation of ERK 1/2 in response to treatment with PE, α₁-AAB from patients or rabbit α₁-AB is shown. (**A**) Cardiomyocytes were treated for 5 and 15 min with 10 µM PE, 2.5 µg/ml α₁-AAB or rabbit α₁-AB, respectively. Equivalent amounts of protein were analyzed by Western blotting with anti-pERK 1/2 antibody (44/42 kD) and the amount of ERK was analyzed with anti-ERK 1/2 antibody. PE, patient α₁-AAB, and rabbit α₁-AB caused ERK 1/2 phosphorylation. (**B**) CHO/α₁ₐ-AR cells were incubated with patient α₁-AAB for 5 min. Lane 1 and 2 represent untreated cells. Patients 1, 4–8 were α₁-AAB-positive in the cardiomyocyte contraction assay. "Patient" 9 represents a pool of five α₁-AAB positive patients. Patients 10–12 were α₁-AAB negative in the cardiomyocyte contraction assay. Their serum samples were processed identically to those of α₁-AAB-positive patients. ERK 1/2 phosphorylation was inhibited by peptide P2, but not by peptide P5. Eukaryotic initiation factor 4E (eIF4E, 25 kD) antibody was used as translational control, the amount of ERK was analyzed with anti-ERK 1/2 antibody.
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Furthermore, rabbit antibody to the α₁AR and autoantibodies against the AT1-receptor could activate the Ca²⁺ current [25,26]. The peak response of cytosolic Ca²⁺ to the antibodies apparently comprises a temporary imbalance of Ca²⁺ entry through L-type Ca²⁺ channel and the sarcoplasmic reticulum Ca²⁺ release on one hand and Ca²⁺ sequestration into the sarcoplasmic reticulum and Ca²⁺ extrusion via the Na⁺/Ca²⁺ exchanger on the other hand.

In addition to acute Ca²⁺ current stimulation, we found that long-term activation of the α₁-AR pathway by patient α₁-AAB and rabbit α₁-AB increases transcript levels of the voltage-dependent L-type Ca²⁺ channel α1C subunit (*Cacna1c*) in neonatal cardiomyocytes and VSMC. Voltage-dependent L-type Ca²⁺ channels (L-VDCC) play a crucial role in the regulation of heart rhythm and contractile performance, as well as in smooth muscle tone. The channels open in response to membrane depolarization providing Ca²⁺ ingress into the cell. In the myocardium, this local rise in Ca²⁺ concentration triggers massive Ca²⁺ release from the sarcoplasmic reticulum stores inducing in turn contraction. L-VDCC expressed in cardiac and smooth muscle are multi-subunit proteins containing the α1C, α2/δ, and β subunits. The α1C subunit forms the ion-selective pore, determines voltage sensitivity, and is a binding site for clinically used Ca²⁺ channel blockers [27]. Thus, upregulation of α1C subunit expression in response to α₁-AR stimulation observed herein provides the route for an enhanced Ca²⁺ ingress which may contribute to Ca²⁺ imbalances and translate in cardiac dysfunction. Our results are consistent with those of Pignier *et al.* who reported on increased expression of functional L-type Ca²⁺ channels and hypertrophy in neonatal cardiomyocytes upon chronic α₁-AR stimulation [28]. In contrast, Maki *et al.* described that in neonatal

rat cardiomyocytes activation of the α₁-AR pathway was accompanied by attenuated α1C mRNA levels [29]. A link between increased α1C protein levels and hypertrophy has also been demonstrated for the human heart [30].

A transgenic mouse with cardiac specific over-expression of solely the Ca²⁺ channel pore subunit has been studied intensively [31]. When α1C protein levels were increased by about 3-fold, a slightly increased Ca²⁺ inward current (30–40%) was observed, and the mice developed hypertrophy and severe cardiomyopathy as a function of age. The small sustained ingress of Ca²⁺ through the channel is capable of elevating PKC-α before the development of hypertrophy. [32] Activation of PKC in adult cardiomyocytes regulates ERK 1/2 through the c-RAF/MEK/ERK signaling pathway and α₁-AR-stimulated hypertrophy in cardiomyocytes is mediated via activation of the Ras-Raf-MEK1/2-ERK 1/2 signaling pathway [6,33]. As a consequence, we investigated the regulation of PKC-α and ERK 1/2 activity by human α₁-AAB, rabbit α₁-AB, or PE. We demonstrated that α₁-AAB and α₁-AB induced PKC-α stimulation and ERK 1/2 phosphorylation. Finally, we showed that human α₁-AAB and the rabbit α₁-AB evoke vasoconstriction in a vascular bed.

Taken together, we present data from a limited, uncontrolled, human trail of α₁-AAB removal from severely hypertensive human subjects. This trial presents a hypothesis-generating result. We show that isolated α₁-AAB from man and rabbits cause gene upregulation important to hypertension-relevant pathways and then document the induction of Ca²⁺-dependent pathways. We provide evidence that α₁-AAB are of potential pathophysiological relevance and could represent a factor contributing to the development of refractory hypertension. Removal or neutralization of α₁-AAB might represent a possible therapeutic option. Accordingly, we suggest that the entire gamut of autoimmunity in chronic cardiovascular disease warrants further critical inspection.

Materials and Methods

Patients

Patients requiring three or more medication classes to achieve goal control blood pressure values were recruited from the Franz-Volhard Clinic outpatient department. All had been studied intensively and secondary causes of hypertension had been ruled out. Home and clinic blood pressures in these patients were determined with an automated oscillometric device under standardized conditions. The internal review board approved the study and written informed consent was obtained from all participants. Five patients harboring α₁-AAB were asked to undergo five immunoadsorption treatments with an especially prepared column according to procedures described elsewhere [34].

α₁-AAB detection

We isolated immunoglobulin fractions from serum samples as described earlier [4,15]. For detection of autoantibodies, the immunoglobulin fractions were added to neonatal rat cardiomyocytes at a dilution of 1:20. For the neutralization experiments, synthetic peptides corresponding to the sequence of the first extracellular loop (YWAFGRVFCNIWA), and the second extracellular loop (PAPEDETICQINEE) of the human α₁ₐ-AR were each added in excess (0.05 to 0.1 µg) to the immunoglobulin fraction. The mixtures were shaken and placed in a refrigerator for 1 h. The 100 µl samples were then added to neonatal rat heart muscle cells cultured in 2 ml of medium to a final dilution of 1:40. The beating rate was counted for 15 sec, 5 and 60 min after the addition of the peptide/immunoglobulin mixture. We tested α₁-AAB activity in a neonatal cardiomyocyte assay without and with

peptide inhibition. Pulsation rate was exhibited 1 h or 24 h, respectively after incubation with α₁-AAB and compared with the spontaneous basal pulsation rate. Eight synchronously contracting cell clusters per flask were counted for 15 sec on a heat table stage.

α₁-AB generation in rabbit and antibody purification

We immunized rabbits against a peptide corresponding to the amino acid sequence of the second extracellular loop of the isoform A of human α₁-AR (PAPEDETICQINEE) by BioGenes GmbH (Berlin, Germany). The corresponding peptide of the second extracellular loop of the α₁-AR was covalently bound to ε-aminocapryl agarose (Sigma-Aldrich, Munich, Germany) to yield epitope-specific affinity beads. For coupling the agarose gel matrix (~1 ml of packed gel) was activated by glutaraldehyde (1% solution, freshly prepared) for 20 min at room temperature on a rotating wheel. The activated gel was extensively washed with PBS and allowed to react with the peptide solution for 3 h at room temperature or overnight at 4°C on a rotating wheel. The coupling reaction was terminated by incubation with 200 mM Tris/Glycine buffer pH 7.2. The affinity beads were poured into a column (Bio-Rad, Munich, Germany) and stored with 0.02% sodium acid in buffer A consisting of 50 mM Tris/HCl, 0.5 M NaCl, pH 7.4, at 4°C.

The affinity beads were washed with buffer A to remove the sodium acid. Serum samples (5–15 ml) from patients with refractory hypertension or from immunized rabbits were incubated with the affinity beads overnight at 4°C on a rotating wheel. The beads were allowed to settle and the sera were removed and stored for a second round of affinity purification at a given matrix. The beads were washed with buffer A until baseline levels of protein are detected at 280 nm. The antibodies were eluted at room temperature in 1 ml fractions with 50 mM Tris/Glycine, 0.5 M NaCl, pH 2.5. Antibody fractions were immediately neutralized with 0.5 ml of 0.5 M Tris/HCl, 0.5 M NaCl, pH 7.4. The antibody concentration was calculated by measurement the absorption at 280 nm.

Surface plasmon resonance measurements

Binding experiments were performed in a BIAcore 2000 Instrument (Uppsala Sweden) at 25°C. N-terminally biotinylated peptides corresponding to the first and second extracellular loop of the α₁A-AR were immobilized at binding levels of 100 relative units (RU) each on parallel lanes of a SA-biosensor chip. Affinity-purified antibodies from patient blood samples were injected in the flow cells at a rate of 20 μl/min in HBSE running buffer consisting of 10 mM HEPES, pH 7.4, 150 mM NaCl, and 3 mM EDTA. The binding was regenerated between binding measurements using 5 mM Tris/Glycine, 50 mM NaCl, pH 2.5, with no decrease in extent measurements over the duration of an experiment. Data were analyzed using the using the BIAevaluation 3.2 RC 1 program. The analysis software corrects for baseline drift during measurements. The curves were fitted to a single-site interaction model. Kd values were calculated by using the formula $Kd = k_{off}/k_{on}$ in which k_{off} and k_{on} is the rate constant of dissociation and association kinetics, respectively.

Cell culture and autoantibody incubation

Rat neonatal cardiomyocytes were prepared from ventricles of 1–2 day-old Wistar rats using a modified method [35]. The cells were cultured as monolayers for 4 days at 37°C in SM 20-1 medium supplemented with 10% heat-inactivated calf serum, 2 μM fluorodeoxyuridine and penicillin/streptomycin. Aortic VSMC were isolated from Sprague Dawley rats as described previously [36]. CHO cells were stably transfected with human α₁A-AR (CHO/α₁A-AR) using a pSW104 vector and were cultured in F12 HAM medium supplemented with glutamine, 10% FCS and 1% penicillin/streptomycin as described earlier [37]. For gene expression analysis cardiomyocytes and VSMC, respectively were incubated with human control IgG endobulin (5 μg/ml medium, Baxter, Wien, Austria), α₁-AAB from different patients (2.5 μg/ml medium), rabbit α₁-AB (2.5 μg/ml medium), and with the α₁-AR agonist PE (10 μM, Sigma-Aldrich) for 24 h in DMEM medium containing 1% serum. Experiments were repeated with three different cardiomyocytes and VSMC preparations. For investigation of protein phosphorylation, cardiomyocytes and CHO/α₁A-AR cells were maintained in serum-free media for 24 h or 4 h, respectively and treated with PE, human α₁-AAB or rabbit α₁-AB for 5 and 15 min, respectively. For inhibition experiments, prazosin (1 μM, Sigma-Aldrich) was added. Five μg of the peptides P2 (APEDET) or P5 (GYVLFS) were given to 2.5 μg of α₁-AAB 1 h before cell treatment. For the inhibition of ERK 1/2 activation, CHO/α₁A-AR cells were pre-incubated with PI3-kinase inhibitor LY294002 for 10 min.

Gene expression analysis

We extracted total RNA from cardiomyocytes treated with human control IgG, α₁-AAB, rabbit α₁-AB or PE using the RNeasy Purification Kit (Qiagen GmbH, Hilden, Germany). RNA was treated by deoxyribonuclease I (Qiagen). Two μg RNA of cells were transcribed in cRNA with One-Cycle Target labeling and Control Reagents (Affymetrix, Santa Clara, CA, USA). Non-pooled microarray experiments were performed with cRNA prepared from independent cardiomyocyte cell preparations using Rat Genome 230 2.0 Arrays (31,099 probe sets, Affymetrix). After passing the quality control for each experiment a set of RMA normalized expression values have been produced. The log scale robust multi-array analysis (RMA) estimates are based upon a robust average of log2 (B (PM)), where B (PM) are background corrected perfect match intensities [38]. For statistical comparison of expression data student's t-test was used.

Quantitative Real-Time Reverse Transcriptase PCR (TaqMan)

cDNA was synthesized from 2 μg of total RNA isolated from cardiomyocytes and VSMC, respectively using PowerScript Reverse Transcriptase (BD Bioscience Clontech, Palo Alto, USA) and an Oligo (dT)₁₈ primer. Real-time PCR experiments were done using the Mx3000P® real-time PCR system (Stratagene Europe, Amsterdam, NL) and the Brillant QPCR master mix (Stratagene Europe). Real-time PCR was performed with non-pooled samples from cardiomyocytes and VSMC respectively. Beta-2-microglobulin (B2M) and glyceraldehyde-3-phosphate dehydrogenase (GAPDH) were used as endogenous references to normalize expression of a target gene. For every sample three independent runs in triplicates and the relative changes in gene expression were quantified by comparative Ct method [39]. Primer sequences are listed in Table 3.

Immunocytochemistry

We described the techniques for confocal microscopy and immunocytochemistry as referenced previously [4,40]. The cells were fixed with 4% paraformaldehyde and permeabilized with 80% methanol at −20°C. After incubation with 2% BSA in PBS for 60 minutes, the preparation was incubated for 1 hour at room temperature with the monoclonal anti-PKC-α antibody from UBI (clone M4) diluted in PBS with 1% BSA (1:80) or pERK 1/2 antibody (1:200, Cell Signaling Technology, Boston, MA, USA), respectively, washed twice with PBS, and then exposed to the secondary antibody (Alexa-488-conjugated anti-mouse IgG at 1:200,

Table 3. Primer and probe sequences used for TaqMan RT-PCR.

Gene		Sequences (5′→3′)	Accession
B2M	for	GCT CGG TGA CCG TGA TCT TT	NM_012512
	rev	GAG TTT TCT GAA TGG CAA GCA	
	probe	FAM-TGG TGC TTG TCT CTC TGG CCG TC-TAMRA	
GAPDH	for	CAA CGG CAC AGT CAA G	NM_017008
	rev	TCG CTC CTG GAA GAT G	
	probe	FAM-TGA GAA TGG GAA GCT GGT CAT CA-TAMRA	
PLA2-IIA	for	GGA CTC CTG CCG GAA ACA G	NM_031598
	rev	TTC CGG GCA AAA CAT TCA G	
	probe	FAM-TGT GCC AGT GCG ATA AAG CTG CC-TAMRA	
Cacna1c	for	TCA CTG CTG TCG GGA TAA GC	NM_012517
	rev	GGC CTT CTC CCC TGA AAA G	
	probe	FAM-AGC TGG GCG GTG TAC GAA GTC G-TAMRA	

Used annealing temperature was 58°C.
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1% BSA/PBS; Invitrogen, Life Technologies, Carlsbad, CA, USA) for 60 minutes. The preparation was mounted with AquaPolymount (Polyscience, Niles, IL, USA) under a glass coverslip on a Nikon-Diaphot microscope. An MRC 1024 confocal imaging system (Bio-Rad) with an argon/krypton laser was used. At least 25 to 40 cells from each of at least three experiments were examined under each experimental condition.

Western blotting

Cardiomyocytes and CHO/α₁A-AR cells were scraped in lysis buffer [20 mM HEPES (pH7.9), 350 mM NaCl, 20% glycerol, 1 mM MgCl2, 0.5 mM EDTA, 0.1 mM EGTA, 1% NP40, complete protease inhibitor cocktail (Roche Diagnostic GmbH, Mannheim, Germany) and phosphatase inhibitor cocktail (Sigma-Aldrich)] and centrifuged at 10,000 rpm for 10 min. Protein concentrations were measured with Bradford method and equal amounts of proteins were analyzed by Western blotting. ERK phosphorylation was detected by pERK 1/2 antibody (1:1000, Cell Signaling Technology). As translational control an ERK antibody (1:1000, Cell Signaling Technology) and eukaryotic initiation factor 4E (elF4E) antibody (1:7000, Cell Signaling Technology) were used. HRP-conjugated goat anti-rabbit secondary antibody (1:5000, Jackson Immunoresearch Europe, Suffolk, UK) was used. Detection was performed with the ECL^TM-substrate (Lumigen, Southfield, MI, USA) according to the manufacturers instructions.

Measurement of cytosolic Ca²⁺ transients

Neonatal cardiomyocytes were plated onto Labtek four chamber slides (Nunc GmbH & Co, Wiesbaden, Germany) suited for fluorescence measurements at a densitiy of 0.2×10^6 cells per chamber. After cultivation for four days the medium was removed and cells were washed twice with 10 mM Hepes-buffered Hank's salt solution, pH 7.4 (HBSS). Cardiomyocytes were incubated on HBSS for 60 minutes at 37°C. Then the solution was replaced by 0.5 ml HBSS containing 2.5 µM final concentration of Fura 2-AM (Calbiochem AG, Luzern, Switzerland) and left for loading in the dark at room temperature. After 30 min the loading solution was aspirated, the cells washed and kept on 0.5 ml HBSS in the dark and at room for another 30 minutes before use. Measurements of cytosolic Ca²⁺ transients were performed on an IonOptix Fluorescence and Contractility System (Milton, MA, USA) equipped with a Leica microscope with a heatable stage. All measurements were carried out at 37°C. Cardiomyocytes were electrically stimulated at 1 Hz and the ratio of 340 nm/380 nm was recorded. After stabilization of the Fura signal the control trace was taken. Antibody preparations were applied in a constant volume of 100 µl of pre-warmed HBSS to give a final concentration of 2 µg/ml. For evaluation of Ca²⁺ changes peak values were derived from the trace recordings representing the maximum cytosolic Ca²⁺ achieved in the contracted cell.

Contraction of mesenteric arteries

Vessel rings from superior mesenteric arteries of male Sprague-Dawley rats (200 to 300 g, 6 to 8 weeks) were prepared and intracellular membrane potential was measured as earlier described [41]. In the first series of experiments, the rings were exposed to increasing doses of PE (10 nM–10 µM) and with acetylcholine (10 nM–10 µM) for relaxation. Following, vessel rings were incubated with α₁-AAB (5 µg in 5 ml PBS buffer), rabbit α₁-AB (50 µg in 5 ml PBS buffer), rabbit IgG (50 µg in 5 ml PBS buffer, Dunn Labortechnik GmBH, Asbach, Germany) and human control IgG endobulin (50 µg in 5 ml PBS buffer).

Statistics

We relied on student's t-tests (adjusted as necessary) for normally distributed data and performed analysis of variance (repeated measures were indicated). $P < 0.05$ was accepted as significant. Data are expressed as mean±SD.

Author Contributions

Conceived and designed the experiments: KW HH GW DNM FCL RD RD PK. Performed the experiments: KW HH GW WD SB VH FH NH HS MJ CL CS SV RD PK. Analyzed the data: KW HH WD SB VH FH NH HS SV IM DNM FCL RD RD PK. Contributed reagents/materials/analysis tools: KW HH GW WD SB IM PK. Wrote the paper: KW HH FCL RD PK.

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