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Age- and Training-Dependent Development of Arrhythmogenic Right Ventricular Cardiomyopathy in Heterozygous Plakoglobin-Deficient Mice

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Background—Arrhythmogenic right ventricular cardiomyopathy (ARVC) is an inherited disorder that causes sudden death and right ventricular heart failure in the young. Clinical data suggest that competitive sports may provoke ARVC in susceptible persons. Genetically, loss-of-function mutations in desmosomal proteins (plakophilin, desmoplakin, or plakoglobin) have been associated with ARVC. To test the hypothesis that reduced desmosomal protein expression causes ARVC, we studied the cardiac effects of heterozygous plakoglobin deficiency in mice.

Methods and Results—Ten-month-old heterozygous plakoglobin-deficient mice (plakoglobin^{+/-}) had increased right ventricular volume, reduced right ventricular function, and spontaneous ventricular ectopy (all $P < 0.05$). Left ventricular size and function were not altered. Isolated, perfused plakoglobin^{+/-} hearts had spontaneous ventricular tachycardia of right ventricular origin and prolonged right ventricular conduction times compared with wild-type hearts. Endurance training accelerated the development of right ventricular dysfunction and arrhythmias in plakoglobin^{+/-} mice. Histology and electron microscopy did not identify right ventricular abnormalities in affected animals.

Conclusions—Heterozygous plakoglobin deficiency provokes ARVC. Manifestation of the phenotype is accelerated by endurance training. This suggests a functional role for plakoglobin and training in the development of ARVC. (*Circulation*. 2006;114:1799-1806.)

Key Words: adherens junctions ■ arrhythmia ■ cardiomyopathy ■ conduction ■ death, sudden ■ desmosomes ■ exercise

Arrhythmogenic right ventricular cardiomyopathy (ARVC) is one of the most common inherited cardiomyopathies and a prevalent cause of ventricular arrhythmias and sudden death in young adults, especially in competitive athletes.¹⁻³ ARVC often presents with ventricular tachycardias of right ventricular origin and causes right ventricular enlargement and dysfunction.^{1,2} Genetic studies have identified mutations in junctional proteins in patients with ARVC, eg, in plakophilin, plakoglobin, desmoglein, and the plakoglobin binding site of desmoplakin.⁴⁻⁹ Most of the mutations are predicted to cause loss of function. Genetically, ARVC is therefore considered a disease of the desmosome.⁵

Editorial p 1794 Clinical Perspective p 1806

Plakoglobin forms part of the mechanical intercellular connections organized in the adherens junctions and desmosomes.¹⁰ Homozygous plakoglobin mutations are associated with Naxos disease, an autosomal-recessive form of ARVC characterized by additional palmo-plantar hyperkeratosis and woolly hair.^{4,11} Expression of dysfunctional, mutated proteins will diminish mechanical adhesion of cardiomyocytes,^{12,13} analogous to the effect of plakoglobin deficiency in keratinocytes.¹³⁻¹⁵ Diminished mechanical adhesion between cardiomyocytes could result in preferential right ventricular

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The online-only Data Supplement, which includes 2 movies, can be found at <http://circ.ahajournals.org/cgi/content/full/CIRCULATIONAHA.106.624502/DC1>.

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dysfunction resulting from the thinner wall of the right ventricle, which may be more sensitive to reduced mechanical stability.

To investigate whether desmosomal dysfunction can be the cause of ARVC, we studied heterozygous plakoglobin-deficient mice (plakoglobin^{+/-12,13}). We found that plakoglobin deficiency provokes the full functional phenotype of ARVC. Aggravation of ARVC by endurance training supports the hypothesis that susceptibility to mechanical cardiac strain contributes to ARVC in this model.

Methods

Transgenic Mice

Heterozygous plakoglobin-deficient mice (plakoglobin^{+/-12,13}) and their wild-type siblings (bred by P.R. and H.W. at the Cardiovascular Research Center, Berlin, Germany) were studied. All functional analyses were performed by researchers blinded to genotype in age- and sex-matched littermate pairs of mice. All experiments were approved by the Institutional Review Board at the University of Muenster.

Cardiac Morphology and Function In Vivo

Sedated mice (diazepam 17.5 mg/kg body weight IP or oxygenated isoflurane 1.5% by inhalation, 37°C body temperature) were studied by a murine echocardiography system (Philips Sonos 5500, Philips, Hamburg, Germany; 15-MHz linear transducer, 12-MHz Doppler transducer¹⁶⁻¹⁸). Cardiac dimensions and function were assessed by M-mode, 2-dimensional, and Doppler echocardiography. Right ventricular measurements derived from a clinical study protocol¹⁹ were used to quantify right ventricular size and volume. Right ventricular measurements were confirmed by cardiac magnetic resonance imaging in selected animals with a 7-T murine magnetic resonance imaging system (Bruker BioSpin MRI GmbH, Ettlingen, Germany).²⁰

ECG in Sedated and Freely Roaming Mice

Twelve-lead surface ECG recordings were obtained and analyzed from sedated mice using published methods (EMKA, Paris, France, or custom-made software).²¹ An ECG in freely moving mice was recorded and analyzed over 24 hours (5 minutes per hour) and during defined stress tests (swimming, warm air jets) 2 weeks after implantation of telemetric ECG transmitters (Data Sciences, St Paul, Minn) as described.^{18,22}

Electrophysiology in Isolated, Langendorff-Perfused Hearts

The heart was excised and immediately perfused on a Langendorff apparatus.^{17,21} The atrioventricular node was ablated to allow for slow ventricular rhythms, and 3 monophasic action potential catheters were simultaneously recorded from the left ventricular free wall, right ventricular free wall, and septal epicardium. Initially, spontaneous rhythm after atrioventricular block was observed. This intervention can provoke spontaneous arrhythmias in susceptible hearts.^{16,21} Thereafter, pacing was performed at 100-, 150-, and 200-ms pacing cycle length to measure steady-state action potential durations and activation times, followed by programmed right ventricular endocardial stimulation using up to 2 premature stimuli.¹⁶ The protocol was repeated during continuous infusion of orciprenaline (1.6 μmol/L).

Myocardial Glucose-Uptake Positron-Emission Tomography

Myocardial glucose uptake was measured in anesthetized mice (inhaled isoflurane 1.5%, 37°C body temperature). Sixty minutes after intravenous injection of 10 MBq [¹⁸F]fluor-desoxy-glucose, the emitted positrons were measured with a high-resolution small-

animal positron-emission tomography camera (quadHIDAC, Oxford Positron Ltd, Oxford, England) for 15 minutes.²³ Images were reconstructed into a matrix with a voxel size of 0.4 mm³. Myocardial glucose metabolism was quantified by dividing myocardial uptake of [¹⁸F]fluor-desoxy-glucose in the left ventricle by the injected dose.

Endurance Training

Four to 6 pairs of littermate mice swam simultaneously in a 30×50-cm-large, 20-cm-deep container containing 35°C water and a floating rotating wheel. Swimming duration was increased from 5 to 90 minutes per day over the 8-week training period (6 d/wk). Daily training intensity was quantified using a semiquantitative activity score defined as follows: running on the floating wheel=2, swimming=1, and floating on the water=0.

Histology, Immunohistochemistry, and Electron Microscopy

Cardiac tissue was fixated in 3.7% formalin and stained with hematoxylin and eosin and Goldner's trichrome staining. Cardiomyocyte diameter was measured in 100 right and left ventricular cells per heart at the level of the nucleus. For immunohistochemistry, 5-μm paraffin sections were dewaxed and rehydrated in a series of alcohols, autoclaved (0.01 mol/L citrate buffer, 45 minutes), and incubated with a plakoglobin antibody (1:1500 in 0.6% bovine serum albumin, Transduction Clone 15, San Diego, Calif). Sections were then incubated with a rabbit anti-mouse bridging antibody (1:30 in phosphate-buffered saline, 45 minutes; Dako, Glostrup, Denmark) and a polyclonal mouse APAAP complex (1:100 in RPMI, 60 minutes; Dianova, Hamburg, Germany) and developed for 25 minutes in new fuchsin solution containing naphthol-bi-as-phosphate and levamisole. Sections were counterstained with hematoxylin and eosin and mounted with Kayser's glycerin gelatin. For electron microscopy, small right and left ventricular tissue samples were fixed in 0.1 mol/L cacodylate-buffered 4% glutaraldehyde for 4 hours at 4°C, postfixated in 1% osmium tetroxide, stained en bloc in 2% uranyl acetate, and embedded in Epon. Semithin sections for light microscopy were stained with toluidine blue. Ultrathin sections were stained with uranyl acetate and lead citrate and examined with a Philips EM 201 transmission electron microscope.

Right Ventricular Gene Expression Analysis

Gene expression analyses were performed in right ventricles taken from 5 severely affected plakoglobin^{+/-} mice and their wild-type littermates (n=4 pairs of trained mice, n=1 pair of 10-month-old mice). Each right ventricular specimen was analyzed separately. Mouse pairs were selected by marked right ventricular enlargement in the plakoglobin^{+/-} sibling on echocardiography. Tissue was rapidly extracted and stored in liquid nitrogen. Amplification and labeling of the RNA samples followed usual protocols (Affymetrix, Santa Clara, Calif). Total RNA was quantified by UV spectroscopy and analyzed on a LabChip (BioAnalyzer, AGILENT Technologies, Santa Clara, Calif). In the presence of an oligo(dT)₂₄ primer containing a T7 RNA polymerase promoter (TIBMOL Biol, Berlin, Germany), 1 to 3 μg total RNA was used for double-stranded cDNA synthesis (SuperScript Transcriptase, Life Technologies, Inc, Carlsbad, Calif). Labeled cRNA was prepared from double-stranded cDNA by in vitro transcription (GeneChip RNA transcript labeling kit, Affymetrix). After cleanup (Qiagen, Hilden, Germany), the biotin-labeled cRNA was fragmented by alkaline treatment (40 mmol/L Tris-acetate [pH 8.2], 100 mmol/L potassium acetate, and 50 mmol/L magnesium acetate) at 94°C for 35 minutes. We hybridized 15 μg of each cRNA sample to Affymetrix RAE 430A GeneChip arrays (22 500 probe sets). Probe arrays were washed and scanned at 3-μm resolution with the Affymetrix GeneChip System Confocal Scanner 2500. Data were analyzed with the Affymetrix GeneChip Operating Software, normalized to a global intensity of 500. Significance analyses of microarrays and hierarchical clustering were used for statistics.

Statistical Analysis

All measurements and analyses were performed by researchers blinded to genotype. All variables are reported as mean \pm SEM. Continuous variables were compared by use of Student *t* test. Both paired and unpaired tests were used to compare results in littermate pairs. The results of paired and unpaired testing were congruent in this study. Two-way ANOVA and regression analyses were used to assess the effect of genotype and age/training on functional parameters. Fisher exact test and χ^2 test were used to compare categorical variables. Two-sided values of $P < 0.05$ were considered significant. SPSS (version 12; SPSS, Inc, Chicago Ill) was used to compute statistics.

The authors had full access to the data and take responsibility for their integrity. All authors have read and agree to the manuscript as written.

Results

Age- and Training-Dependent Right Ventricular Enlargement in Plakoglobin^{+/-} Mice

At the age of 10 months, right ventricles were enlarged in plakoglobin^{+/-} mice (Figure 1A and 1B and Table). Endurance training (8 weeks of daily swimming) caused premature right ventricular dilatation and dysfunction in plakoglobin^{+/-} mice at 5 to 6 months of age (Figure 1 and Table). Training intensity was not different between plakoglobin^{+/-} and wild-type mice. Training intensity correlated with training-induced right ventricular enlargement in plakoglobin^{+/-} mice (Figure 2B). There was no difference in left ventricular size or function between genotypes. Right heart size (Table) and function (Figure 1C and 1D) were not different between genotypes at earlier ages. Cardiac glucose uptake as assessed by positron-emission tomography was normal in plakoglobin^{+/-} mice (3-month-old mice [n=8 per genotype]: plakoglobin^{+/-} $3.8 \pm 1.6\%$ versus wild-type $3.5 \pm 1.9\%$ of injected dose, $P=0.77$; trained mice [n=12 per genotype]: plakoglobin^{+/-} $3.8 \pm 1.3\%$ versus wild-type $3.2 \pm 1.2\%$, $P=0.18$). There were no excess deaths in plakoglobin^{+/-} mice in this study.

Spontaneous Ventricular Arrhythmias in Freely Roaming Plakoglobin^{+/-} Mice

Ten-month-old plakoglobin^{+/-} mice showed increased spontaneous ventricular ectopy (Figure 3; during normal activity, plakoglobin^{+/-} 0.64 ± 0.3 ventricular premature beats [VPBs] per hour versus wild-type 0.35 ± 0.2 VPBs per hour, $P=0.48$; during stress, plakoglobin^{+/-} 2.19 ± 0.6 VPBs per hour versus wild-type 1.26 ± 0.5 VPBs per hour; $P=0.14$). Ventricular arrhythmias were not increased in younger plakoglobin^{+/-} mice.

Spontaneous Ventricular Tachycardias of Right Ventricular Origin in 10-Month-Old and Trained Plakoglobin^{+/-} Mouse Hearts

Spontaneous ventricular tachycardias were frequent in 10-month-old and trained plakoglobin^{+/-} hearts (Figure 4). Arrhythmias were self-terminating in all but 2 plakoglobin^{+/-} hearts and in all wild-type hearts. Arrhythmia duration was 12.2 ± 6.7 seconds (minimal duration, 0.3 seconds; maximal duration, 132 seconds) in 21 plakoglobin^{+/-} hearts and 3.2 ± 0.7 seconds (minimal duration, 0.4 seconds; maximal duration, 6.4 seconds) in 8 littermate wild-type hearts. In

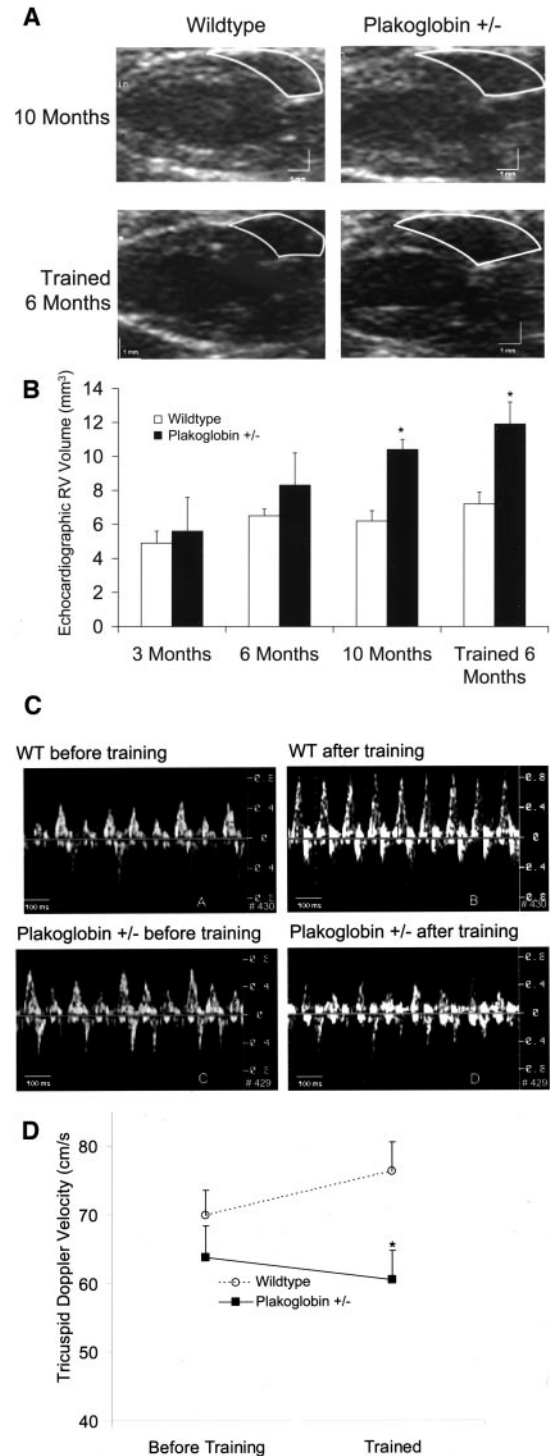


Figure 1. Age- and training-dependent increased right ventricular volume and reduced right ventricular function in plakoglobin^{+/-} mice. A, Representative 2-dimensional long-axis echocardiography of a 10-month-old and a trained plakoglobin^{+/-} mouse and their wild-type controls. The right ventricle is marked by the white line. B, Mean right ventricular volumes in plakoglobin^{+/-} and wild-type mice. C, Representative transtricuspid Doppler flow in a 10-month-old and a trained plakoglobin^{+/-} mouse and their wild-type controls. D, Mean transtricuspid Doppler flow velocity before and after training in plakoglobin^{+/-} and wild-type mice (n=8 per genotype). Two-way ANOVA using age/training status and genotype confirmed that genotype affected right ventricular volume ($P=0.007$) and transtricuspid Doppler flow ($P=0.026$) after training.

Right Ventricular Enlargement and Dysfunction in 10-Month-Old and Trained Plakoglobin^{+/-} Mice

	3 Months (9–12 Weeks)		6 Months (22–26 Weeks)		Trained (22–26 Weeks)		>10 Months (>42 Weeks)	
	Wild Type	Plakoglobin ^{+/-}	Wild Type	Plakoglobin ^{+/-}	Wild Type	Plakoglobin ^{+/-}	Wild Type	Plakoglobin ^{+/-}
Doppler echocardiography, n	8	9	9	9	16	19	15	21
Tricuspid valve diameter, mm	1.9±0.1	2.2±0.2	2.1±0.1	2.2±0.02	2.2±0.07	2.2±0.1	2.1±0.08	2.5±0.1
RV area 4-chamber view, mm ²	...	...	5±0.5	7±0.5	7±0.6	10±1.1*	7±0.4	11±0.4*
RV area long-axis view, mm ²	5±0.5	6±1.4	7±0.5	7±0.6	6±0.3	7±3*	5±0.3	7±0.3*
RV area short-axis view, mm ²	4±0.4	6±2.4	4±0.4	5±0.6	4±0.5	5±1	3±0.2	5±0.2*
Heart rate, bpm	464±16	434±35	474±22	479±10	417±13	424±11	509±36	486±35
Left atrial size (long-axis view), mm	1.8±0.1	1.9±0.1	2.5±0.7	2.5±0.8	2.4±0.1	2.3±0.1	2.4±0.1	2.5±0.1
Diastolic septal thickness, mm	0.8±0.03	0.9±0.05	0.9±0.06	0.9±0.05	0.9±0.04	0.9±0.04	0.9±0.03	0.9±0.04
LV end-diastolic diameter, mm	3.2±0.08	3.0±0.1	3.2±0.1	3.2±0.2	3.3±0.1	3.2±0.1	3.1±0.11	3.2±0.1
LV end-systolic diameter, mm	1.6±0.1	1.5±0.1	1.6±0.1	1.6±0.1	1.6±0.1	1.5±0.1	1.6±0.1	1.6±0.1
LV fractional shortening, %	51±2	48±4	51±2	50±3	51±1	52±1	48±3	52±3
LV ejection fraction, %	84±2	80±4	83±2	82±2	83±1	84±1	79±3	82±2
LV cardiac output, mL/min	15.3±2	15.0±2	15.5±1	13.8±1	16.3±1	16.4±2	13.7±2	16.1±1
LV stroke volume, μL	50±4	60±8	60±6	50±3	60±3	60±3	50±4	50±3
Mitral valve Doppler E/A ratio	1.3±0.1	1.4±0.1	1.2±0.04	1.2±0.03	1.4±0.04	1.3±0.06	1.6±0.1	2.1±0.3
Mitral valve deceleration time, ms	35±3	36±3	28±3	29±2	38±9	36±7	34±3	39±2
LV mass, mg	71±3	78±6	94±3	93±3	96±5	97±5	94±6	105±6
Maximal aortic flow, cm/s	117±3	131±22	92±5	95±5	98±5	99±5	82±7	95±6
Cardiac MRI	...	...	...	...	n=4	n=4	...	...
RV ejection fraction, %	...	...	...	...	77±2	59±5*	...	...
RV cardiac output, mL/min	...	...	...	...	19±1	13±0.8*	...	...
Cardiomyocyte diameter (histology), n	4	2	...	...	6	11	4	8
RV cardiomyocyte diameter, μm	11.3±0.7	10.4±1.1	...	...	10.6±1.0	11.7±2.5	10.6±0.7	10.7±0.6
LV cardiomyocyte diameter, μm	14.4±1.2	14.1±1.5	...	...	14.6±0.9	14.2±1.0	15.1±1.2	13.2±0.9
Electrophysiological measurements, n	...	...	16	24	14	15	7	10
RV APD70, 100-ms cycle length	...	...	26.1±4.0	26.2±2.3	32.6±2.3	27.7±3.8	23.6±2.5	23.8±1.5
LV APD70, 100-ms cycle length	...	...	27.3±1.8	30.4±2.5	28.1±2.6	26.2±2.1	23.2±2.9	27.8±1.7
RV APD70, 200-ms cycle length	...	...	22.8±2.3	28.2±2.5	30.1±3.3	28.6±1.6	27.3±2.8	25.2±1.5
LV APD70, 200-ms cycle length	...	...	28.7±2.3	29.6±1.9	25.9±1.9	25.6±2.0	28.4±2.4	25.6±1.5

RV indicates right ventricular; LV, left ventricular; MRI, magnetic resonance imaging; and APD, action potential duration. All data are given as mean±SE.

*Significant differences from wild-type mice.

plakoglobin^{+/-} hearts, ventricular arrhythmias originated from the right ventricular free wall or septum, as evident from the site of earliest activation in the first tachycardia beat, but never from the left ventricular free wall (Figure 5). Spontaneous arrhythmias in wild-type hearts originated in equal proportions from the 3 recording sites.

Right Ventricular Conduction Slowing in 10-Month-Old and Trained Plakoglobin^{+/-} Mice

Right ventricular activation times were prolonged in 10-month-old and trained plakoglobin^{+/-} mouse hearts, ie, the conditions associated with ventricular tachycardias (Figure 5B). Left ventricular activation times and right and left ventricular action potential durations were not different between genotypes (Table).

Normal Right Ventricular Structure in Old and Trained Plakoglobin^{+/-} Hearts

There was no sign of increased fibrosis, cardiomyocyte hypertrophy (Table), or replacement of myocardium with

fibrofatty tissue in right ventricles of affected plakoglobin^{+/-} mice (n=4 ten-month-old mice, n=10 trained plakoglobin^{+/-} mice) compared with wild-type littermates. Desmosomal and adherens junctions' structure was not different between genotypes (electron microscopy; Figure 6). Connexin43 distribution and density were not altered in immunohistochemical images stained for connexin43 (n=8 plakoglobin^{+/-} hearts selected by marked phenotype and wild-type littermates; data not shown).

Right Ventricular Gene Expression Profiling in Plakoglobin^{+/-} and Wild-Type Mice

Training induced expression of several hypertrophy-associated genes (Figure 2A). The expression patterns between wild-type and plakoglobin^{+/-} samples were not different, even when different statistical approaches, eg, combination of littermates (significant analysis of microarrays: 1 class response) or calculation with logarithmic or linear expression values, were used. Hierarchical clustering

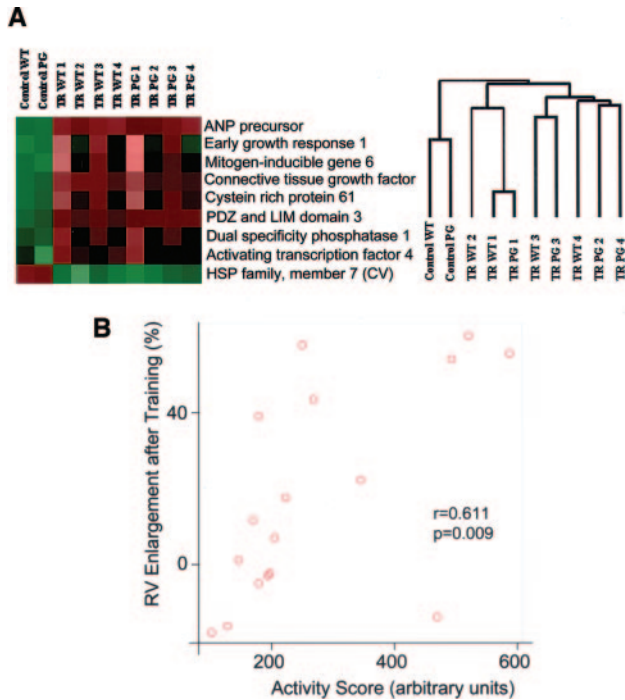


Figure 2. Effect of training on right ventricular gene expression and right ventricular size. A, Differential expression of selected hypertrophy-associated genes in 4 pairs of trained wild-type (TR WT) and plakoglobin^{+/-} mice (TR PG) compared with two 10-month-old mice (Control WT and Control PG, left) and hierarchical clustering based on the expression values of all samples (right). B, Linear correlation between training intensity, measured as activity index (x axis), and training-induced increase in right ventricular long-axis area (y axis) in plakoglobin^{+/-} mice.

of the 10 samples using all “expressed” genes (≈ 8800 gene tags) separated between untrained control mice and trained mice but not between genotypes (Figure 2A, right). Expression data are accessible at <http://www.ncbi.nlm.nih.gov/projects/geo/> (GEO number GSE4120).

Discussion

Age- and Training-Dependent Development of ARVC in Plakoglobin^{+/-} Mice

The present study demonstrates for the first time that reduced expression of the junctional protein plakoglobin is sufficient for the development of an ARVC-like phenotype. These data strongly support the pathophysiological concept derived from genetic abnormalities of junctional proteins in ARVC patients^{4–6,24,25} that decreased expression and function of junctional proteins is a key element in the genetic predisposition to ARVC. Furthermore, endurance training can worsen right ventricular function and provoke right ventricular arrhythmias in this murine model of reduced plakoglobin expression. These data support the recommendation that patients with ARVC should avoid endurance training.²⁶ Different individual degrees of physical activity could contribute to incomplete penetrance or untypical manifestation of ARVC in patients carrying mutations in desmosomal proteins.⁷

Similar to patients with ARVC,^{1,2} old and trained plakoglobin^{+/-} mice developed ventricular arrhythmias of right ventricular origin. This is of special note because Naxos

Ventricular Premature Beats (VPB)

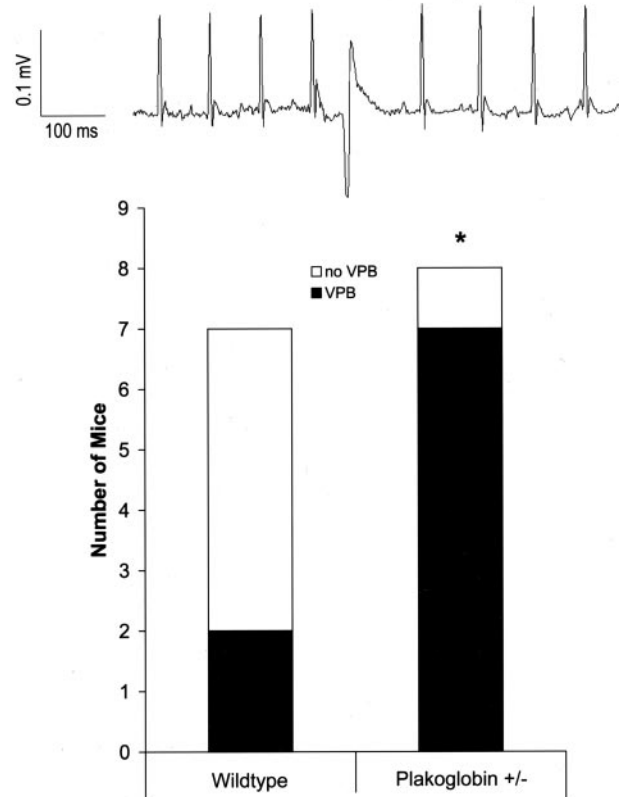


Figure 3. Ventricular arrhythmias in freely roaming plakoglobin^{+/-} mice. Spontaneous VPBs (inset) and number of mice with spontaneous VPBs during 1 hour of telemetric ECG recording under normal laboratory conditions. There were more plakoglobin^{+/-} mice (right bar) than wild-type mice (left bar) with VPBs.

disease, the clinical entity with mutations in the plakoglobin gene, is an autosomal-recessive form of ARVC.⁴ The most prominent electrophysiological abnormality was conduction slowing in the right ventricle (Figure 5), consistent with prolonged QRS duration in the signal-averaged ECG in ARVC patients.²⁷ In contrast, cardiac repolarization was not altered in plakoglobin^{+/-} mice.

It is usually assumed that right ventricular conduction slowing in ARVC, including Naxos disease,^{28,29} is due to anatomic barriers (focal fibrofatty replacement)¹ or to markedly reduced cardiac connexin43 expression. Much to our surprise,^{1,28,29} we found neither fibrofatty replacement of right ventricular myocardium nor reduced connexin43 expression or altered gene expression profiles in affected right ventricles from plakoglobin^{+/-} hearts. Hypothetically, this discrepancy could have 3 explanations. First, the histological changes found in ARVC patients—often analyzed postmortem—may develop later than the functional changes, concordant with occasional reports that the clinical cardiac manifestations of Naxos disease may develop without histological abnormalities in the heart in younger patients.^{7,28} Second, the structural abnormalities found in ARVC patients may be due to genetic abnormalities other than those resulting in plakoglobin deficiency. Third, abnormal function of mutated junctional proteins (as opposed to reduced levels of normal

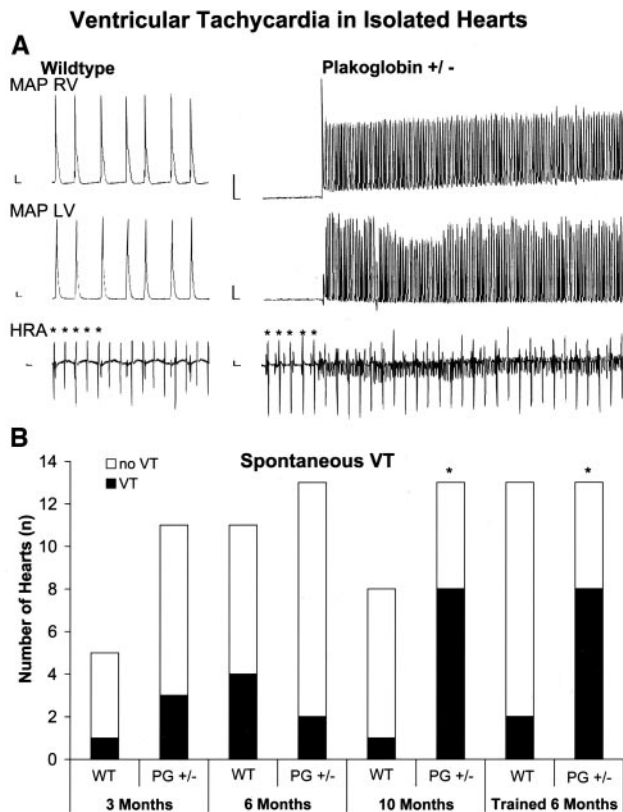


Figure 4. Spontaneous ventricular tachycardia (VT) in isolated plakoglobin^{+/-} mouse hearts. A, Recording of 2 simultaneous right ventricular (RV) and left ventricular (LV) epicardial monophasic action potentials and of a right atrial endocardial electrogram in a wild-type (left) and a plakoglobin^{+/-} mouse heart (right) after experimental atrioventricular nodal block. The wild-type heart shows a regular ventricular escape rhythm. The plakoglobin^{+/-} heart shows a sustained polymorphic VT. Asterisks mark atrial activations. All calibration bars indicate 100 ms and 1 mV. B, Number of hearts with VT (solid bars) and without VT (open bars) in each age group and genotype with and without training. The 10-month-old and trained plakoglobin^{+/-} hearts more often had VT than wild-type hearts.

proteins in our model) may cause the structural changes in ARVC.

Further studies are required to elucidate the relation between functional and structural changes in different models and populations of ARVC.

Comparison With Other Models of Disrupted Myocardial Intercellular Connections

Our findings contrast to those in laminin-receptor 1-deficient mice, which develop fibrofatty replacement of the right ventricles, although their cardiac electrophysiology has not been studied.³⁰ Heart-directed³¹ or inducible³² disruption of N-cadherin causes loss of intercalated disks, marked reduction in connexin43 expression, and ventricular arrhythmias.³¹ In contrast to N-cadherin, plakoglobin is a linker protein that connects the cytoplasmic portion of the desmosomes and adherens junctions to the intracellular mechanical structure formed by actin and intermediate filaments.¹⁵ Concordant with this functional difference, the functional consequences of N-cadherin deficiency differ from those of plakoglobin

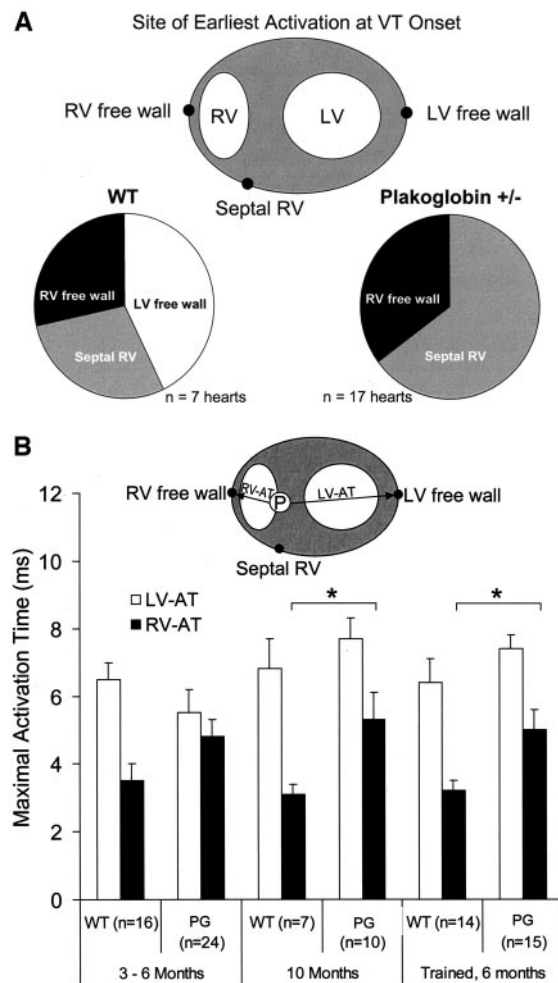


Figure 5. Right ventricular origin of ventricular arrhythmias and right ventricular conduction slowing in plakoglobin^{+/-} mice. A, Proportion of hearts with earliest activation of the first beat of ventricular tachycardia (VT) in the right ventricular (RV free wall), septal (RV septal), and left ventricular (LV free wall) monophasic action potential recording. The upper scheme indicates the recording locations in a cross section of the heart. All VT episodes originated from right ventricular recording sites in plakoglobin^{+/-} hearts. B, Prolonged right ventricular but not left ventricular conduction in 10-month-old and trained plakoglobin^{+/-} hearts. The upper scheme indicates the stimulation and recording sites for measurement of right and left ventricular conduction times. Bar graph indicates mean right (black bars) and left (white bars) ventricular conduction times for each of the study groups.

deficiency: Inducible disruption of N-cadherin reduces left ventricular function,³² and plakoglobin deficiency causes right ventricular dysfunction (Figure 1). Heart-directed N-cadherin deficiency causes inducible ventricular arrhythmias³¹; plakoglobin deficiency causes spontaneous ventricular arrhythmias (Figures 3 and 4).

Plakoglobin Deficiency: A Functional Defect That Causes ARVC?

Reduced plakoglobin expression could hypothetically reduce adhesive forces in the heart,³³ comparable to the effect of plakoglobin deficiency in keratinocytes,¹⁴ which may be attributed to a reduced number of functional desmosomes¹² and to reduced mechanical contacts between desmosomes

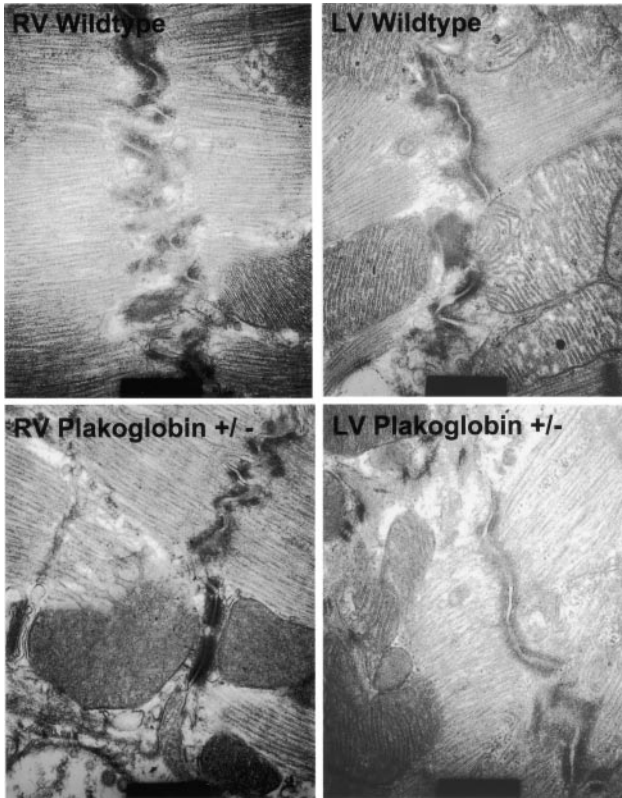


Figure 6. Normal junctional structure in right and left ventricles of plakoglobin^{+/-} mice. Electron microscopic images of intercalated disks in right ventricular (RV) and left ventricular (LV) myocardium from an affected plakoglobin^{+/-} and wild-type control ventricle. Magnification $\times 30\,000$.

and the intracellular cytoskeleton.^{12,13} These changes could potentially predispose to right ventricular enlargement secondary to passive distension of the right ventricular wall and to slow right ventricular conduction secondary to reduced mechanical contact between cardiomyocytes.

The physiological response to endurance training includes an upregulation of plakoglobin.^{14,34} The deficiency of 1 plakoglobin allele appears to be sufficient to cause the phenotypic changes we report here. This suggests that the intact allele is not sufficient for normal cardiac plakoglobin function. In addition to an abnormal response to myocardial wall stress, a reduced myocardial fiber compliance³³ could contribute to premature right ventricular dilatation in trained plakoglobin^{+/-} hearts comparable to the intrauterine right ventricular rupture found in homozygous plakoglobin^{-/-} mice.¹³

Conclusions

Deletion of 1 plakoglobin allele profoundly alters right ventricular contractile and electrophysiological function without affecting myocardial structure, desmosomal contact appearance, or connexin43 expression. Further studies are warranted to delineate the subcellular mechanisms by which reduced plakoglobin expression causes right ventricular enlargement and arrhythmias and to investigate the cause for the structural abnormalities in ARVC. Because ARVC is pheno-

typically and genetically a heterogeneous disease, this will require studies in different models and populations of ARVC.

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Disclosures

None.

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CLINICAL PERSPECTIVE

Arrhythmogenic right ventricular cardiomyopathy (ARVC) is an inherited cardiomyopathy and a prevalent cause of sudden death in the young. The disease is characterized by dilatation and dysfunction of the right ventricle. Ventricular tachycardias of right ventricular origin are often its first manifestation. The most prominent histopathological finding is fibrofatty replacement of right ventricular myocardium. Genetic studies have consistently demonstrated defects in genes coding for desmosomal proteins (plakophilin 2, desmoglein, plakoglobin, and others) in affected families and patients, suggesting that ARVC is a disease of the desmosome. The present article reports the first functional proof of this concept: Mice with heterozygous deletion of the desmosomal protein plakoglobin develop right ventricular dilatation, dysfunction, and arrhythmias. The present study has additional clinically relevant aspects. First, physical training accelerated the development of the ARVC phenotype in this model, consistent with the clinical suspicion that competitive, and especially endurance, sports can aggravate ARVC. Second, the full functional phenotype of ARVC developed without detectable histological changes in plakoglobin-deficient mice. This surprising finding requires further study but highlights the concept that ARVC is due to functionally altered intercellular connections. Finally, plakoglobin mutations have so far been found only in patients with Naxos disease, an autosomal-recessive form of ARVC. The present study suggests that deletion of 1 plakoglobin allele may be sufficient to develop the phenotype of ARVC. Together with the published genetic data, the present study suggests that desmosomal dysfunction is a key factor in the development of right ventricular dysfunction.