Low Myocardial Protein Kinase G Activity in Heart Failure with Preserved Ejection Fraction

Running title: van Heerebeek et al.; Myocardial PKG in HFPEF

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Abstract:

**Background** - Prominent features of myocardial remodeling in heart failure with preserved ejection fraction (HFPEF) are high cardiomyocyte resting tension ($F_{\text{passive}}$) and cardiomyocyte hypertrophy. In experimental models, both reacted favourably to raised protein kinase G (PKG) activity. The present study assessed myocardial PKG activity, its downstream effects on cardiomyocyte $F_{\text{passive}}$ and cardiomyocyte diameter and its upstream control by cyclic guanosine monophosphate (cGMP), nitrosative/oxidative stress and brain natriuretic peptide (BNP). To discern altered control of myocardial remodeling by PKG, HFPEF was compared to aortic stenosis (AS) and HF with reduced EF (HFREF).

**Methods and Results** - Patients with HFPEF (n=36), AS (n=67) and HFREF (n=43) were free of coronary artery disease. More HFPEF patients were obese (p<0.05) or had diabetes (p<0.05). LV myocardial biopsies were procured transvascularly in HFPEF and HFREF and perioperatively in AS. $F_{\text{passive}}$ was measured in cardiomyocytes before and after PKG administration. Myocardial homogenates were used for assessment of PKG activity, cGMP concentration, proBNP-108 expression and nitrotyrosine expression, a measure of nitrosative/oxidative stress. Additional quantitative immunohistochemical analysis was performed for PKG activity and nitrotyrosine expression. Lower PKG activity in HFPEF than in AS (p<0.01) or HFREF (p<0.001) was associated with higher cardiomyocyte $F_{\text{passive}}$ (p<0.001) and related to lower cGMP concentration (p<0.001) and higher nitrosative/oxidative stress (p<0.05). Higher $F_{\text{passive}}$ in HFPEF was corrected by in-vitro PKG administration.

**Conclusions** - Low myocardial PKG activity in HFPEF was associated with raised cardiomyocyte $F_{\text{passive}}$ and was related to increased myocardial nitrosative/oxidative stress. The latter was probably induced by the high prevalence in HFPEF of metabolic comorbidities. Correction of myocardial PKG activity could be a target for specific HFPEF treatment.

**Key words:** diastole; heart failure; myocytes; natriuretic peptides; nitric oxide
Introduction

Despite modern heart failure (HF) therapy, prognosis of heart failure with preserved ejection fraction (HFPEF) did not improve over the last decades. This epidemiological finding confirmed the neutral result of numerous large outcome trials testing modern pharmacotherapy in HFPEF. The neutral outcome of these trials has been variably ascribed to trial design and to failure to address features of myocardial dysfunction and remodeling prominently present in HFPEF.

Prominent clinical features of myocardial dysfunction in HFPEF are slow relaxation and high diastolic stiffness. High diastolic stiffness is also present in muscle strips and single cardiomyocytes isolated from LV myocardium of HFPEF patients. Slow relaxation and high diastolic stiffness have both been shown to react favourably to raised PKG activity following in-vivo administration of sildenafil, which raises myocardial PKG activity through inhibited breakdown of cyclic guanosine monophosphate (cGMP) by phosphodiesterase 5A (PDE5A).

Sildenafil restored LV relaxation kinetics in mice exposed to transverse aortic constriction (TAC) and reduced diastolic LV stiffness in an old hypertensive dog model, in patients with HF and reduced EF (HFREF) and in HFPEF patients with pulmonary hypertension. Administration of sildenafil to old hypertensive dogs lowered diastolic LV stiffness through restored phosphorylation of the N2B segment of titin, which was recently shown to be hypophosphorylated in HF patients and to have PKG phosphorylation sites. Prominent features of myocardial remodeling in HFPEF are cardiomyocyte hypertrophy and interstitial fibrosis. Modulation of the soluble guanylate cyclase (sGC)-PKG-PDE5A axis also affected myocardial remodeling with less cardiomyocyte hypertrophy and interstitial fibrosis in TAC mice exposed to sildenafil.

Because of these promising experimental and clinical effects of sildenafil on myocardial
dysfunction and remodeling in HFPEF and because of the ongoing large outcome trial testing sildenafil in HFPEF (RELAX study;ClinicalTrials.gov IdentifierNCT00763867), the present study measured PKG activity, upstream control of PKG activity and downstream effects of PKG activity in LV myocardial biopsies of HFPEF patients. To discern altered control by PKG of the myocardial remodeling process in HFPEF, measurements were compared to measurements obtained from LV myocardium remodeled concentrically by severe aortic stenosis (AS) or eccentrically by nonischemic HFREF.

**Methods**

**Patients**

HF patients had been hospitalized for worsening HF and referred for cardiac catheterization and transvascular LV endomyocardial biopsy procurement because of suspicion of infiltrative or inflammatory myocardial disease. Patients were included if coronary angiography ruled out significant epicardial coronary artery stenosis (>50%), and if histological examination of the biopsy showed no evidence of infiltrative or inflammatory myocardial disease. The HF patient study cohort consisted of 79 patients of whom 36 were classified as HFPEF and 43 as HFREF. Patients were diagnosed as HFPEF if LVEF>50%, LV end-diastolic volume index <97mL/m² and LV end-diastolic pressure>16 mmHg. Patients were classified as HFREF if LVEF<45%. No HF patient had cardiac resynchronization therapy or a LV assist device. The AS group consisted of 67 patients with symptomatic AS (mean aortic valve area 0.53±0.04 cm²) and without significant coronary disease. In this group, LV biopsy material consisted of LV endomyocardial tissue resected from the LV outflow tract (Morrow procedure) because of concomitant LV outflow tract narrowing. Hemodynamic data of HFREF, HFPEF and AS
patients are listed in the Table. LVPSP, LVEDP, LVEDVI and LVEF were derived from biplane LV angiograms. PWTd and LVMI were derived from 2-dimensional echocardiograms. The local ethics committee approved the study protocol. Written informed consent was obtained from all patients and there were no complications related to procedure or biopsy procurement.

**Histomorphometric myocardial analysis**

Histomorphometric analysis of biopsy samples was performed on hematoxylin-and-eosin-stained, 4 µm-thick sections of tissue placed in 5% formalin. Images of these sections were acquired with a projection microscope(X200) and subsequently analyzed with Slidebook 4.0 software(31, Denver,Colorado) to determine cardiomyocyte diameter(MyD;µm;17.1±1.5 cardiomyocytes measured per patient) and reactive interstitial fibrosis, expressed as collagen volume fraction(CVF;%;4.1±0.3 representative fields per patient)7,15.

**Force measurements in isolated cardiomyocytes**

Force measurements were performed in single, mechanically isolated cardiomyocytes as described previously (2.6±0.1 cardiomyocytes per patient).6,7,12. Biopsy samples(5 mg wet weight) were defrosted in relaxing solution, mechanically disrupted, and incubated for 5 minutes in relaxing solution supplemented with 0.2% Triton X-100 to remove all membrane structures. Single cardiomyocytes were stretched to a sarcomere length of 2.2 µm to measure passive force (F\text{passive}). In HFPEF patients, F\text{passive} measurements were repeated after 40 minutes incubation in relaxing solution containing PKG1α(0.1 U/mL;Sigma,batch034K1336) and cyclic guanosine monophosphate(cGMP)(10 µmol/L,Sigma).

**Myocardial PKG activity**

Myocardial PKG activity was assessed in homogenized tissue samples. Tissues samples were homogenized in 25 mmol/l Tris (pH 7.4), 1 mmol/l EDTA, 2 mmol/l EGTA, 5 mmol/l
Staining was visualized using 3,3'-diaminobenzidine (DAB, 0.1 mg/ml, 0.02% H₂O₂). Sections with anti-mouse/rabbit Envision (undiluted; K5007; Dako Cytomation) for 30 minutes at RT. All incubations were done for 1 hour at room temperature (RT). Samples were then incubated with anti-VASP antibody (A-11; 1:50; sc-46668, Santa Cruz Biotechnology, Inc) for detection of VASP. Antibody (16C2; #676602, Calbiochem) for detection of pVASP, and with mouse monoclonal anti-Ser239 pVASP antibody (Promega) and a highly specific inhibitor of cAMP-dependent protein kinase (5-24, Calbiochem). The reaction mixtures were incubated at 30°C for 10 min, followed by termination of the reaction by spotting 70 μl of the reaction mix onto Whatman P-81 filters, which were then soaked with 75 mmol/l H₃PO₄ for 5 min and washed three times with 75 mmol/l H₃PO₄ to remove any unbound [³²P]ATP. Filters were rinsed with 100% ethanol and air dried before quantification. For quantification of PKG activity, counts were taken in a Wallac 1409 Liquid Scintillation Counter using universal scintillation cocktail (ICN). Specific activity of PKG was expressed as pmol of [³²P] incorporated into the substrate (pmol/min/mg protein).

Immunohistochemical analysis was performed on formalin-fixed tissue sections. Myocardial PKG activity was measured immunohistochemically by ratio of vasodilatory-stimulated phosphoprotein (VASP) phosphorylated at Ser²³⁹ (pVASP) to total VASP (pVASP/VASP ratio)¹⁶. Biopsy samples were stained with mouse monoclonal anti-Ser²³⁹ pVASP antibody (16C2; #676602, Calbiochem) for detection of pVASP, and with mouse monoclonal anti-VASP antibody (A-11; 1:50; sc-46668, Santa Cruz Biotechnology, Inc) for detection of VASP. All incubations were done for 1 hour at room temperature (RT). Samples were then incubated with anti-mouse/rabbit Envision (undiluted; K5007; Dako Cytomation) for 30 minutes at RT. Staining was visualized using 3,3'-diaminobenzidine (DAB, 0.1 mg/ml, 0.02% H₂O₂). Sections were then counterstained with hematoxylin, dehydrated and covered. With each staining a PBS
control or an irrelevant antibody was used. All these controls yielded negative results. pVASP and VASP levels were calculated, using Slidebook 4.0 software, as respective myocardial positive staining areas relative to total myocardial area (4.8±0.4 representative fields per patient).

**Myocardial cGMP concentration**

Myocardial cGMP was determined in homogenates by use of parameter™ cGMP assay immunoassay kit (R&D Systems, Minneapolis, Minn), in which cGMP present in the homogenate competes with fixed amount of horseradish peroxidase (HRP)-labeled cGMP for sites on a rabbit polyclonal antibody. The homogenates were diluted in cell lysis buffer and 100μl of 0.025μg/μl protein aliquots were assayed according to manufacturer’s instructions. Results of duplicate determinations were averaged and expressed as pmol/ml.

**Myocardial nitrotyrosine, proBNP-108, sGC and PDE5A expression**

Gel electrophoresis and Western blot were performed to analyse expression of nitrotyrosine protein (dilution 1:1000, upstate) and proBNP-108 (dilution 1:500, NOVUS Biologicals). Biopsies were resuspended in 1 ml cold 10% trichloroacetic acid solution (TCA, dissolved in acetone containing 0.1% (w/v) dithiothreitol (DTT)). TCA treated tissue pellets were homogenized in sample buffer containing 15% glycerol, 62.5 mM Tris (pH 6.8), 1% (w/v) SDS and 2% (w/v) DTT. Samples (dry weight) were applied in a concentration that was within the linear range of detection. After 1D separation, proteins were transferred to Hybond ECL nitrocellulose membranes. Blots were preincubated with 0.5% milk powder or 3% bovine serum albumin in TTBS (Tween Tris-buffered saline; 10 mmol/l Tris-HCl pH 7.6, 75 mmol/l NaCl, 0.1% Tween) for one hour at room temperature. The blots were incubated overnight at 4°C with primary rabbit polyclonal antibodies against nitrotyrosine (dilution 1:500, NOVUS Biologicals) and proBNP-108. After washing with TTBS, primary antibody binding was visualized using a
secondary horseradish peroxidase-labeled, goat-anti-rabbit or goat-anti-mouse (dilution 1:1000; DakoCytomation) and enhanced chemiluminescence (ECL Western blotting detection, Amersham Biosciences). All signals were normalized to actin (dilution 1:1000; clone KJ43A; Sigma) stained on the same blots. Staining was visualized using the LAS-3000 Image Reader (460 nm/605 nm Ex/Em; 2 s illumination) and signals were analyzed with AIDA software.

Myocardial nitrotyrosine content was also assessed immunohistochemically with biopsy samples stained with mouse monoclonal anti-nitrotyrosine antibody (HM.11,1:50,ab7048, Abcam). Myocardial nitrotyrosine levels were calculated as respective myocardial staining areas relative to total myocardial area (representative fields per patient: 9.7±1.2).

For detection of myocardial sGC and PDE5A levels, biopsy samples were stained with rabbit polyclonal guanylate cyclase beta1 antibody(1:100,ab24824,Abcam) and rabbit polyclonal PDE5A antibody(1:10,ab14672,Abcam) respectively. Myocardial sGC and PDE5A levels were calculated as respective myocardial positive staining areas relative to total myocardial area (representative fields per patient: sGC 6.9±1.0; PDE5A 22.7±3.5). For immunohistochemical assessment of nitrotyrosine content and sGC or PDE5A expression, incubation procedures, secondary antibodies and visualization techniques were similar to the aforementioned immunohistochemical assessment of pVASP or VASP.

**Statistical analysis**

Values are given as mean±SEM. A 2-tailed test with a probability of value <0.05 was considered significant. Single comparisons were assessed by an unpaired Student t test. Bonferroni-adjusted t tests were used subsequent for multiple comparisons after ANOVA. If Levene test revealed unequal variances, unequal-variance t test or Welch’s ANOVA was used. The significance for categorical variables was determined by the Fisher’s exact test. Statistical analysis was
performed with SPSS (Version 15.0; SPSS Inc, Chicago, Ill).

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

Results

Clinical, hemodynamic and echocardiographic characteristics

Hypertension was more prevalent in HFPEF than in HFREF and diabetes mellitus (DM) was more prevalent in HFPEF than in AS (Table). HFPEF patients had a higher BMI than both HFREF and AS patients. In both HF groups, there was more frequent use of ACE-I and/or ARBs, diuretics and digoxin. Aldosterone receptor antagonists were used more frequently in HFREF than in HFPEF and AS, while statins were used less frequently in HFREF than in HFPEF and AS. There was a progressive rise of LVPSP, LVEF and LVMI/LVEDVI from HFREF to HFPEF and to AS, and a progressive fall of LVEDVI from HFREF to HFPEF and to AS. LVEDP was similar in all three conditions. PWTd was equally elevated in HFPEF and AS compared to HFREF.

Force measurements in isolated cardiomyocytes

Cardiomyocyte $F_{\text{passive}}$ was higher in HFPEF (7.6±0.4 kN/m²; n=18) than in AS (3.4±0.2 kN/m²; n=39; p<0.001) and in HFREF (5.1±0.2 kN/m²; n=22; p<0.001) (Figure 1A, 1B). When patients were subdivided in accordance to absence or presence of DM (Table) (DM⁻; DM⁺), $F_{\text{passive}}$ was higher in HFPEF-DM⁻ than in AS-DM⁻ or HFREF-DM⁻ and also higher in HFPEF-DM⁺ than in AS-DM⁺ or HFREF-DM⁺ (Supplementary Figure). After administration of PKG, $F_{\text{passive}}$ fell significantly in HFREF, HFPEF and AS (Figure 1B). The fall in $F_{\text{passive}}$ was significantly larger in HFPEF than in AS or HFREF (Figure 1C). $F_{\text{passive}}$ of normal human cardiomyocytes is...
2.8±0.1 kN/m² and remains unchanged after PKG administration (2.6±0.1 kN/m²).6,12.

Myocardial PKG activity and cGMP concentration

PKG activity in myocardial tissue homogenates was significantly lower in HFPEF (5.11±0.62 pmol/min/mg; n=12) than in both AS (9.18±0.64 pmol/min/mg; n=12; p<0.01) and HFREF (11.51±2.0 pmol/min/mg; n=12; p<0.001) (Figure 2A). In subsets of DM⁻ and DM⁺ patients, PKG activity was lower in HFPEF-DM⁻ than in AS-DM⁻ or HFREF-DM⁻ and also lower in HFPEF-DM⁺ than in HFREF-DM⁺ (Supplementary Figure). Immunohistochemical determination of myocardial PKG activity by pVASP/VASP ratio provided confirmatory evidence as it was also significantly lower in HFPEF (0.70±0.03; n=9) than in both AS (0.84±0.02; n=18; p<0.001) and HFREF (0.85±0.03; n=14; p<0.001) (Figure 2B, 2C). Myocardial cGMP concentration was significantly lower in HFPEF (11.0±0.7 pmol/ml; n=18) than in both AS (98.9±13.9 pmol/ml; n=20; p<0.001) and HFREF (168.8±23.6 pmol/ml; n=22; p<0.001) (Figure 3). In subsets of DM and DM⁺ patients, cGMP concentration was lower in HFPEF-DM⁻ than in AS-DM⁻ or HFREF-DM⁻ and also lower in HFPEF-DM⁺ than in AS-DM⁺ or HFREF-DM⁺ (Supplementary Figure).

Myocardial nitrotyrosine, proBNP-108, sGC and PDE5A expression

Unequal nitrotyrosylation of proteins in HFPEF (n=12), AS (n=16) and HFREF (n=18) myocardium was investigated for proteins ranging from 240 kDa to 10 kDa. Strong differential nitrotyrosylation (HFPEF: 0.34±0.08 a.u.; AS: 0.05±0.02 a.u.; p<0.01; HFREF: 0.10±0.03 a.u., p<0.01) was observed in a 66 kDa protein (Figure 4A) and weak differential nitrotyrosylation in 210 kDa and 20 kDa proteins. None of these proteins was identified. Immunohistochemical determination of myocardial nitrotyrosine content was also significantly higher in HFPEF (3.94±0.24%) than in both AS (3.26±0.13%; p<0.05) and HFREF (2.64±0.24%; p<0.001) (Figure 4B, 4C). When HFPEF, AS and HFREF patients were pooled, myocardial nitrotyrosine content
related to cardiomyocyte $F_{\text{passive}}$ ($r=0.68$; $p=0.016$). Myocardial proBNP-108 expression was significantly lower in HFPEF (0.22±0.07 a.u.; $n=12$) than in HFREF (0.76±0.26 a.u.; $n=16$; $p<0.05$) and similar in HFPEF and AS (0.18±0.05 a.u.; $n=16$) (Figure 5). Immunohistochemical analysis demonstrated similar myocardial expression levels of sGC (HFPEF: 3.67±0.38%, $n=4$; AS: 3.37±0.14%, $n=6$; HFREF 3.93±0.34%, $n=4$) and PDE5A (HFPEF: 20.4±1.0%, $n=6$; AS: 21.4±0.8%, $n=7$; HFREF 23.3±1.3%, $n=5$) in all groups.

Histomorphometric myocardial analysis

MyD was similarly elevated in HFPEF (28.1±0.2μm; $n=12$) and AS (28.7±0.3μm; $n=18$), but lower in HFREF (24.7±0.3μm; $n=21$; $p<0.001$ vs HFPEF). CVF was comparable in HFPEF (11.3±0.3%; $n=31$) and HFREF (12.2±0.4%; $n=36$), but higher in AS (14.1±1.1%; $n=33$; $p=0.002$ vs HFPEF).

Discussion

The present study reveals reduced PKG activity and lower cGMP concentration in concentrically remodeled LV myocardium of HFPEF patients than in concentrically remodeled myocardium of AS patients and than in eccentrically remodeled LV myocardium of HFREF patients. Reduced PKG activity and lower myocardial cGMP concentration in HFPEF did not result from altered myocardial sGC or PDE5A expression, which was similar in all groups nor from unequal natriuretic peptide (NP) expression, which was comparable in HFPEF and AS. The downregulated cGMP-PKG signaling in HFPEF was more likely related to low myocardial nitric oxide (NO) bioavailability because of high nitrosative/oxidative stress. High nitrosative/oxidative stress in HFPEF was inferred in the present study from the higher myocardial nitrotyrosine content in HFPEF than in both HFREF and AS. Lower PKG activity affected myocardial
dysfunction in HFPEF as evident from the higher cardiomyocyte $F_{\text{passive}}$ in HFPEF and the correction of this higher $F_{\text{passive}}$ by in-vitro administration of PKG.

**Myocardial PKG signaling in HFPEF**

The present study is the first to comprehensively compare myocardial PKG activity, its downstream effects on cardiomyocyte stiffness and hypertrophy and its upstream control by cGMP, sGC, PDE5A, nitrosative/oxidative stress and proBNP-108 in different forms of human cardiac remodeling, consisting respectively of HFPEF and AS associated concentric remodeling and of HFREF associated eccentric remodeling. Upregulated PDE5A expression was previously observed in remodeled human myocardial tissue procured at cardiac surgery from hypertrophied right ventricles of congenital cardiac malformations or at cardiac transplantation from explanted dilated or ischemic cardiomyopathic hearts. Although PDE5A and sGC enzyme activities were not directly measured in the present study, the lower PKG activity and cGMP concentration in HFPEF than in AS or HFREF can not be ascribed to higher expression of PDE5A nor to lower expression of sGC or proBNP-108. They therefore probably derived from lower myocardial NO bioavailability because of higher nitrosative/oxidative stress, which is known to directly impair NO-cGMP-PKG signaling. In the present study, higher nitrosative/oxidative stress was inferred from higher myocardial nitrotyrosine content in HFPEF than in both HFREF and AS. The higher myocardial nitrosative/oxidative stress observed in the HFPEF patients of the present study could be related to the higher prevalence of comorbidities associated with elevated oxidative stress, such as obesity and DM (Table). Previous epidemiological studies already reported HFPEF to be associated with obesity or DM, both of which have also been implicated in diastolic LV dysfunction.
Initial clinical studies on the myocardial contractile effects of NO already observed NO to acutely improve LV relaxation and diastolic stiffness\textsuperscript{26}. This beneficial action of NO on diastolic LV function was explained by PKG-dependent phosphorylation of troponin-I or titin and PKG-independent phosphorylation of phospholamban. PKG-dependent phosphorylation of the giant cardiomyocyte cytoskeletal protein titin is of special interest as PKG-induced phosphorylation of its N2B segment lowers $F_{\text{passive}}$ in human HF cardiomyocytes\textsuperscript{12} or in cardiomyopathic myocardial strips\textsuperscript{13}. The present study establishes lack of cardiomyocyte PKG activity as an important contributor to myocardial diastolic dysfunction in HFPEF as it observed lower myocardial PKG activity in HFPEF to correspond with higher cardiomyocyte $F_{\text{passive}}$ and in-vitro administration of PKG to acutely lower the high $F_{\text{passive}}$ of HFPEF cardiomyocytes. Apart from PKG-dependent control of diastolic LV dysfunction in HFPEF, the present study also supports involvement of nitrosative/oxidative stress. Such involvement has also been suggested in recent experimental and clinical studies. Oxidative stress leads to formation of disulfide bridges within the titin molecule, which raises its overall stiffness\textsuperscript{27}. In a mouse HFPEF model, oxidative stress uncouples cardiac NOS and induces diastolic LV dysfunction\textsuperscript{28}. Finally, high plasma levels of methylated L-arginine metabolites were strongly related to diastolic LV dysfunction in patients with HFREF\textsuperscript{29}. Accumulation in circulating blood of methylated L-arginine metabolites mainly results from oxidative stress inhibiting their breakdown by dimethylarginine dimethylaminohydrolase\textsuperscript{30}.

**PKG activity and myocardial remodeling in HFPEF**

In LV cardiomyocytes cultured from neonatal rat hearts, NO or a cGMP analogue attenuated the norepinephrine-induced hypertrophic response through modulation of $Ca^{++}$ influx\textsuperscript{31}. NO or a cGMP analogue exerted these effects by raising PKG activity, which suppressed prohypertrophic...
calcineurin-NFAT signaling\textsuperscript{32}. These in-vitro findings were in line with subsequent in-vivo experiments in mice subjected to TAC\textsuperscript{8}. In these mice, sildenafil raised myocardial PKG activity and prevented or reversed cardiomyocyte hypertrophy and interstitial fibrosis by deactivating multiple prohypertrophic pathways\textsuperscript{8}. Furthermore, in a transgenic mouse model, cardiomyocyte-specific PDE5 overexpression induced an exaggerated hypertrophic and fibrotic response to LV pressure-overload, which was reversed by enhancing cGMP-PKG activity through suppressed PDE5 gene expression\textsuperscript{33}. The ability of cGMP-PKG activity to dampen maladaptive hypertrophy during LV pressure overload was however seriously challenged by recent experiments showing deletion of PKG to have no effect on maladaptive myocardial hypertrophy in mice subjected to TAC\textsuperscript{34}. The present study failed to observe relations between myocardial PKG activity and MyD or CVF, when HFPEF patients were compared to HFREF and AS. This failure could relate to different prohypertrophic signaling pathways prevailing in the different conditions\textsuperscript{35} and to more frequent use in the present study of ACE-Is, ARBs and aldosterone receptor antagonists in HF than in AS. The finding in AS of PKG activity corresponding with $F_{\text{passive}}$ but not with MyD, suggests cardiomyocyte diastolic stiffness to evolve independently from cardiomyocyte hypertrophy. This concept also emerged from the VALIDD trial, in which only 3\% of hypertensives had significant LV hypertrophy despite all having diastolic LV dysfunction\textsuperscript{36}.

**Therapeutic Implications**

Treatment of HFPEF remains uncertain as many large outcome trials yielded neutral results. These neutral results were variably explained by flawed trial design and testing of treatment paradigms extrapolated from HFREF\textsuperscript{3}. By observing lower PKG activity and higher nitrotyrosine level in HFPEF myocardium, the present study supports use in HFPEF of NO-donors, PDE5 inhibitors and drugs with antioxidative properties such as statins. Acute administration of NO
donors is known to ameliorate diastolic LV function\textsuperscript{26} while chronic use of isosorbide dinitrate combined with the antioxidant hydralazine improved outcome in V-HeFT I and A-HeFT trials\textsuperscript{37,38}. The clinical characteristics of the A-HeFT HFREF patients revealed a high prevalence of obesity and diabetes\textsuperscript{39}. HFPEF patients have a similar clinical profile and the present study provides direct evidence for high myocardial oxidative stress in HFPEF. Combined use of isosorbide dinitrate and the antioxidant hydralazine could therefore be potentially favourable in HFPEF.

In HFREF, acute administration of sildenafil ameliorated cardiac performance by lowering LV load\textsuperscript{40} and in both HFREF and HFPEF, chronic administration ameliorated diastolic LV dysfunction\textsuperscript{10,11}. The effect on diastolic LV dysfunction contributed respectively to improved clinical status in HFREF and reduced pulmonary hypertension in HFPEF. Acute administration of sildenafil was recently also reported to lower diastolic LV stiffness and to increase myocardial titin phosphorylation in an old hypertensive HFPEF dog model\textsuperscript{9} and chronic administration of sildenafil was previously demonstrated to improve TAC-induced concentric LV remodeling in mice\textsuperscript{8}. Because of these encouraging, clinical and experimental results, sildenafil has been proposed as a potential therapy for HFPEF\textsuperscript{2,35}. The present study however suggests no superior effectiveness of sildenafil in HFPEF as myocardial expression of PDE5A was similar in all patient groups.

In the present study, myocardial proBNP-108 expression was comparable between HFPEF and AS and higher in HFREF than in both HFPEF and AS. These observations are consistent with proBNP-108 expression being regulated by diastolic LV wall stress, which is higher in HFREF because of eccentric LV remodeling and similar in HFPEF and AS because of concentric LV remodeling\textsuperscript{41}. Because of comparable proBNP-108 expression in HFPEF and
AS, BNP is unlikely to account for the widely different PKG activities and cGMP concentrations observed in both conditions, which were therefore attributed to higher nitrosative/oxidative stress in HFPEF than in AS. Lower proBNP-108 expression in HFPEF than in HFREF also explains the low positive predictive value of BNP for the diagnosis of HFPEF. Acute BNP administration was recently reported to lower diastolic LV stiffness and to increase myocardial titin phosphorylation in an old hypertensive HFPEF dog model but failed to improve clinical endpoints in acutely decompensated HF patients with LVEF ≥ 40%.43

Finally, the present study supports use of statins in HFPEF because of their antioxidative properties. In experimental hypertensive HF, statins were known to exert a variety of favourable actions on concentric myocardial remodeling such as regression of LV hypertrophy and prevention of myocardial fibrosis. Moreover, usefulness of statins in HFPEF was already demonstrated in a preliminary study that showed statins to lower mortality with a relative risk reduction of 22%.45

**Limitations**

The “in-vivo” relevance of low myocardial PKG activity for diastolic LV dysfunction in HFPEF is currently only supported by the lower diastolic LV stiffness observed in an old hypertensive HFPEF dog model following administration of sildenafil or BNP and still needs to be clinically confirmed by mechanistic studies and large outcome trials.

Myocardial ischemia was excluded only by absence of significant (>50%) epicardial coronary artery stenosis. In a concentrically remodeled left ventricle, which was present in both HFPEF and AS patients, absence of significant coronary artery stenosis does not exclude subendocardial ischemia at the site of biopsy procurement. Subendocardial ischemia because of concentric LV remodeling is however an unlikely cause for the higher F_{passive} in HFPEF because...
AS patients had a higher LVMI/LVEDVI ratio but a lower $F_{\text{passive}}$ than HFPEF patients.

Because of the higher prevalence of DM in the HFPEF patients, higher $F_{\text{passive}}$ and lower myocardial PKG activity or cGMP concentration could have resulted from DM-induced upregulation of oxidative stress. In a subset analysis of DM$^-$ and DM$^+$ patients, the findings in the DM$^-$ patients however resembled the overall results. This confirms the higher $F_{\text{passive}}$ and lower PKG activity or cGMP concentration in HFPEF to be associated with the HFPEF phenotype and not with a higher prevalence of DM in the HFPEF group. Furthermore, the findings in the DM$^+$ patients also resembled the overall results apart from low PKG activity in the AS-DM$^+$ patients. The latter finding was however consistent with a recent report on DM worsening diastolic LV dysfunction and raising $F_{\text{passive}}$ in aortic stenosis$^{15}$.

Finally, immunohistochemical quantification of PKG activity using pVASP phosphorylated at Ser$^{239}$ lacks specificity as Ser$^{239}$ can also be phosphorylated by PKA. It therefore only provides confirmatory evidence of the PKG enzyme activity measurements performed on tissue homogenates.

Conclusions

HFPEF myocardium is characterized by downregulated NO-cGMP-PKG signalling probably because of high nitrosative/oxidative stress. Low PKG activity raises cardiomyocyte stiffness and is a potential target for a specific HFPEF treatment strategy.

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Conflict of Interest Disclosures: None
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### Table. Clinical, Hemodynamic and Echocardiographic Characteristics.

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<thead>
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<th></th>
<th>HFREF (n=43)</th>
<th>HFPEF (n=36)</th>
<th>AS (n=67)</th>
<th>p-value (HFPEF vs HFREF)</th>
<th>p-value (HFPEF vs AoS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>60.0±2.1</td>
<td>63.8±2.0</td>
<td>65.3±1.6</td>
<td>0.21</td>
<td>0.57</td>
</tr>
<tr>
<td>Male, (%)</td>
<td>70</td>
<td>56</td>
<td>47</td>
<td>0.24</td>
<td>0.53</td>
</tr>
<tr>
<td>Hypertension, (%)</td>
<td>16</td>
<td>78</td>
<td>58</td>
<td>&lt;0.0001</td>
<td>0.07</td>
</tr>
<tr>
<td>Diabetes mellitus, (DM,%)</td>
<td>30</td>
<td>47</td>
<td>26</td>
<td>0.16</td>
<td>0.047</td>
</tr>
<tr>
<td>Body mass index, (BMI;kg/m²)</td>
<td>27.5±0.8</td>
<td>30.4±1.0</td>
<td>28.1±0.6</td>
<td>0.023</td>
<td>0.031</td>
</tr>
<tr>
<td>Body surface area, (BSA;m²)</td>
<td>1.91±0.03</td>
<td>1.94±0.04</td>
<td>1.77±0.03</td>
<td>0.57</td>
<td>0.002</td>
</tr>
<tr>
<td>Atrial fibrillation, (%)</td>
<td>33</td>
<td>14</td>
<td>2</td>
<td>0.067</td>
<td>0.028</td>
</tr>
<tr>
<td>Medication</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACE-I/ARB, (%)</td>
<td>81</td>
<td>81</td>
<td>43</td>
<td>1.00</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Betablocker, (%)</td>
<td>63</td>
<td>53</td>
<td>61</td>
<td>0.49</td>
<td>0.52</td>
</tr>
<tr>
<td>Diuretic, (%)</td>
<td>72</td>
<td>78</td>
<td>54</td>
<td>0.61</td>
<td>0.028</td>
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<tr>
<td>Aldosterone receptor antagonist, (%)</td>
<td>74</td>
<td>47</td>
<td>7</td>
<td>0.020</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Digoxin, (%)</td>
<td>33</td>
<td>14</td>
<td>2</td>
<td>0.067</td>
<td>0.028</td>
</tr>
<tr>
<td>Statin, (Stat;%)</td>
<td>21</td>
<td>42</td>
<td>46</td>
<td>0.054</td>
<td>0.83</td>
</tr>
<tr>
<td>Metformin, (%)</td>
<td>14</td>
<td>17</td>
<td>3</td>
<td>0.76</td>
<td>0.049</td>
</tr>
<tr>
<td>Bronchodilators, (%)</td>
<td>19</td>
<td>17</td>
<td>9</td>
<td>1.00</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Hemodynamics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR, (beats/min)</td>
<td>82±4</td>
<td>75±2.0</td>
<td>74±2.0</td>
<td>0.073</td>
<td>0.71</td>
</tr>
<tr>
<td>LVPSP, (mmHg)</td>
<td>120±3</td>
<td>166±6</td>
<td>223±4</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LVEDP, (mmHg)</td>
<td>22.3±1.4</td>
<td>25.1±1.1</td>
<td>22.8±1.4</td>
<td>0.12</td>
<td>0.21</td>
</tr>
<tr>
<td>LVEDVI, (ml/m²)</td>
<td>127±5</td>
<td>80±3</td>
<td>55±2</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LVEF, (%)</td>
<td>29.4±1.5</td>
<td>58.4±2.1</td>
<td>64.0±1.2</td>
<td>&lt;0.0001</td>
<td>0.016</td>
</tr>
<tr>
<td><strong>Echocardiography</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWTd, (mm)</td>
<td>9.56±0.32</td>
<td>11.0±0.26</td>
<td>11.0±0.23</td>
<td>0.0011</td>
<td>0.93</td>
</tr>
<tr>
<td>LVM/LVEDVI</td>
<td>1.03±0.06</td>
<td>1.74±0.07</td>
<td>2.55±0.17</td>
<td>&lt;0.0001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

ACE-I, angiotensin converting enzyme inhibitor; ARB, angiotensin II receptor blocker; HR, heart rate; LVPSP, LV peak-systolic pressure; LVEDP, LV end-diastolic pressure; LVEDVI, LV end-diastolic volume index; LVEF, LV ejection fraction; PWTd, diastolic posterior wall thickness; LVM/LVEDVI, LV mass index.
Figure Legends:

**Figure 1.** A: single cardiomyocyte mounted between force transducer and piezoelectric motor; B: higher cardiomyocyte $F_{\text{passive}}$ in HFPEF than in HFREF or AS with a significant fall in $F_{\text{passive}}$ after PKG administration in all three conditions; C: larger fall in cardiomyocyte $F_{\text{passive}}$ after PKG administration in HFPEF than in HFREF or AS.

**Figure 2.** A: lower PKG activity in myocardial tissue homogenates in HFPEF than in HFREF or in AS; B: representative immunohistochemical images stained for pVASP and VASP in HFREF, HFPEF and AS; C: lower myocardial PKG activity assessed by immunohistochemical pVASP/VASP ratio in HFPEF than in HFREF or in AS.

**Figure 3.** Lower myocardial cGMP concentration in HFPEF than in HFREF or in AS.

**Figure 4.** A: Higher nitrotyrosylation of a 66kDa protein in HFPEF than in HFREF or AS, assessed by Western blot analysis and normalized for actin; B: representative immunohistochemical images stained for nitrotyrosine in HFREF, HFPEF and AS; C: higher myocardial nitrotyrosine content assessed by quantitative immunohistochemistry in HFPEF than in HFREF or in AS.

**Figure 5.** Left hand panel: Myocardial proBNP-108 expression, assessed by Western blot analysis and normalized for actin, is lower in HFPEF than in HFREF and similar in HFPEF and AS; right hand panel: representative Western blot lanes showing myocardial proBNP-108 and actin expression.
Figure A: Image showing a microscopic view with a scale bar indicating 20 μm.

Figure B: Bar charts comparing F_{passive} (kN/m²) across different conditions:
- HFREF
- HFREF+PKG
- HFPEF
- HFPEF+PKG
- AS
- AS+PKG

Statistical significances are indicated as:
- p<0.001
- p<0.01
- p<0.05

Figure C: Bar charts showing ΔF_{passive after PKG} (kN/m²) for:
- HFREF
- HFPEF
- AS

Statistical significances are indicated as:
- p<0.05
- p<0.01
Myocardial pVASP/VASP ratio

A

PKG enzyme activity (pmol/min/mg protein)

HFREF HFPEF AS

p < 0.001 p < 0.01

B

C

Myocardial pVASP/VASP ratio

HFREF HFPEF AS
p < 0.001  p < 0.001

<table>
<thead>
<tr>
<th></th>
<th>cGMP (pmol/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFREF</td>
<td>200</td>
</tr>
<tr>
<td>HFPEF</td>
<td>5</td>
</tr>
<tr>
<td>AS</td>
<td>100</td>
</tr>
</tbody>
</table>
ProBNP-108/actin (a.u.)

HFREF  HFPEF  AS

p < 0.05

ProBNP-108
Actin

HFREF  HFPEF  AS

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SUPPLEMENTAL MATERIAL

Low Myocardial Protein Kinase G Activity in Heart Failure with Preserved Ejection Fraction

by Van Heerebeek L. et al.

CirculationAHA/2011/076075
Supplemental Figure: Patients are subdivided in accordance to absence (DM\(^-\)) or presence (DM\(^+\)) of diabetes mellitus (HFPEF-DM\(^-\): n=19; HFPEF-DM\(^+\): n=17; HFREF-DM\(^-\): n=30; HFREF-DM\(^+\): n=13; AS-DM\(^-\): n=50; AS-DM\(^+\): n=17). HFPEF-DM\(^-\) patients had higher cardiomyocyte $F_{\text{passive}}$ and lower myocardial PKG enzyme activity or cGMP concentration than AS-DM\(^-\) or HFREF-DM\(^-\) patients. HFPEF-DM\(^+\) patients had higher cardiomyocyte $F_{\text{passive}}$ and lower cGMP concentration than AS-DM\(^+\) or HFREF-DM\(^+\) patients. HFPEF-DM\(^+\) patients also had lower PKG enzyme activity than HFREF-DM\(^+\) patients.