HIGHLIGHTED TOPIC | Exploring New Concepts in the Management of Heart Failure with Preserved Ejection Fraction: Is Exercise the Key for Improving Treatment?

Myocardial hypertrophy and its role in heart failure with preserved ejection fraction

Frank R. Heinzel,1 Felix Hohendanner,1 Ge Jin,2,3 Simon Sedej,3 and Frank Edelmann1

1Department of Cardiology, Charité-Universitätsmedizin Berlin, Campus Virchow-Klinikum, Berlin, Germany; 2Cardiology Department, The Second Affiliated Hospital & YuYing Children’s Hospital of Wenzhou Medical University, Wenzhou, Zhejiang, P. R. China; and 3Division of Cardiology, Medical University of Graz, Graz, Austria

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Heinzel FR, Hohendanner F, Jin G, Sedej S, Edelmann F. Myocardial hypertrophy and its role in heart failure with preserved ejection fraction. J Appl Physiol 119: 1233–1242, 2015. First published July 16, 2015; doi:10.1152/japplphysiol.00374.2015.—Left ventricular hypertrophy (LVH) is the most common myocardial structural abnormality associated with heart failure with preserved ejection fraction (HFrEF). LVH is driven by neurohumoral activation, increased mechanical load, and cytokines associated with arterial hypertension, chronic kidney disease, diabetes, and other comorbidities. Here we discuss the experimental and clinical evidence that links LVH to diastolic dysfunction and qualifies LVH as one diagnostic marker for HFrEF. Mechanisms leading to diastolic dysfunction in LVH are incompletely understood, but may include extracellular matrix changes, vascular dysfunction, as well as altered cardiomyocyte mechano-elastical properties. Beating cardiomyocytes from HFrEF patients have not yet been studied, but we and others have shown increased Ca2+ turnover and impaired relaxation in cardiomyocytes from hypertrophied hearts. Structural myocardial remodeling can lead to heterogeneity in regional myocardial contractile function, which contributes to diastolic dysfunction in HFrEF. In the clinical setting of patients with compound comorbidities, diastolic dysfunction may occur independently of LVH. This may be one explanation why current approaches to reduce LVH have not been effective to improve symptoms and prognosis in HFrEF. Exercise training, on the other hand, in clinical trials improved exercise tolerance and diastolic function, but did not reduce LVH. Thus current clinical evidence does not support regression of LVH as a surrogate marker for (short-term) improvement of HFrEF.

HFrEF; diastolic dysfunction; left ventricular hypertrophy; cardiac myocytes; remodeling

LEFT VENTRICULAR HYPERTROPHY: CLINICAL PRESENTATION

Heart failure with preserved ejection fraction (HFrEF) or diastolic heart failure (DHF; as it has been classically referenced) is common, of increasing prevalence, and causes a substantial reduction in prognosis. In the majority of patients with symptomatic HFrEF, a history of hypertensive heart disease, including changes in left ventricular (LV) geometry, such as myocardial hypertrophy, can be found. Myocardial hypertrophy is defined as an increase in ventricular myocardial mass. In clinical practice and in animal studies, LV hypertrophy (LVH) is often assessed by measurement of end-diastolic thickness of septal and LV posterior wall and may be associated with normal or dilated LV cavity. Based on the assessment of the ratio of LV wall thickness and LV internal diameter (relative wall thickness), altered LV geometry in LVH has been classified into three groups: concentric remodeling (enlarged heart with normal relative wall thickness), concentric hypertrophy (increased relative wall thickness, normal internal diameter), and eccentric hypertrophy (increased relative wall thickness, increased internal diameter) (65). In clinical trials, LV mass (LVM) is the most common parameter of LVH and is estimated by algorithms subtracting the volume of the LV cavity from the volume enclosed by the epicardium. LVM, as assessed by echocardiography, is related to body surface area.
CAUSES AND CONSEQUENCES OF LVH

LVH has long been regarded as a natural response to stabilize LV function in the presence of triggers that increase mechanical (after-) load, such as arterial hypertension or aortic stenosis (31). Indeed, according to Laplace’s law \( \text{LV pressure} \times \text{LV radius}/(2 \times \text{LV wall thickness}) \), an increase in LV wall thickness lowers the tension (pressure) acting on the individual myocardial cell. However, the concept of LVH as a compensatory mechanism has been challenged based on clinical observations, as well as experimental models. Clinically, the degree of LVH has been associated with worse outcome (34, 56, 67). LVH [by electrocardiography (ECG)] has been found to be a predictor of sudden cardiac death, and the risk increases with LVH, independent of other risk factors (including coronary artery disease and heart failure) (34). In the Framingham Heart Study and other clinical trials, LVH based on ECG or echocardiographic criteria has been suggested as an independent cardiovascular risk factor (34, 67).

Furthermore, diuretics, nonnitrate vasodilators (e.g., diltiazem or prazosin), and inotropes that improve symptoms and hemodynamics of hypertensive heart disease, but not LVH, are generally not associated with improved prognosis in heart failure (11). Most importantly, in animal models of heart failure, pharmacological and genetic interference with hypertrophic signaling cascades did not promote decompensation, but rather were beneficial for LV function and survival (22, 42).

LVH is also observed in athletes as a consequence of repetitive vigorous exercise (or in case of the python snake also by consumption of an extended meal) and during pregnancy (3). However, in the athlete’s heart, hypertrophy is not associated with increased fibrosis or apoptosis and results in normal or increased cardiac function and normal survival (12). Experimental data indicate that it is the type of trigger, not the duration, that initiates signaling for either physiological or maladaptive LVH (92). For instance, chronic exercise training as a physiological stimulus results in an increased level of growth hormone and subsequently insulin-like growth factor I, which mediates cardiomyocyte growth and survival via the phosphoinositide 3-kinase pathway (59, 97). This type of physiological LVH is not associated with diastolic dysfunction or worse prognosis (8, 69, 119) and is not a focus of this review.

Comorbidities, such as arterial hypertension, diabetes, or chronic kidney disease, which promote LVH (107, 112), are common in heart failure patients with preserved as well as with reduced ejection fraction (HFrEF). LVH is also often observed in HFrEF (mostly concentric LVH) and HFrEF (often eccentric). However, there is strong and growing cumulative evidence that HFrEF and HFrEF represent different disease entities, as reviewed recently (55). Paulus and Tschöpe (89) have recently proposed a new paradigm, which suggests fundamental differences in the mechanisms that drive LV remodeling and contractile dysfunction in HFrEF and HFrEF. Accordingly, a chronic systemic inflammatory disease state and associated cardiac mesenchymal alterations promote contractile dysfunction in HFrEF, whereas HFrEF is driven by dysfunction intrinsic to the cardiomyocytes. Figure 1 combines these observations and shows the pivotal role of LV hypertrophic remodeling in both disease entities. LVH following loss of cardiomyocytes (e.g., acutely with myocardial infarction or chronically with idiopathic cardiomyopathy) often results in HFrEF (red arrows), which is in line with distinct signaling pathways. Vice versa, concentric LVH as a result of multiple cardiovascular risk factors is a common cause for HFrEF (blue arrows) and in clinical settings (as opposed to many experimental models) only infrequently transitions to HFrEF (14, 70). However, eccentric hypertrophy in HFrEF is also observed and potentially indicates a distinct subgroup of patients who may develop HFrEF (50). Alterations at the cardiomyocyte level during LVH contribute to the heart failure pheno-

![Fig. 1. Role of left ventricular (LV) hypertrophy in heart failure. Based on Ref. 89, heart failure with preserved (HFrEF) and reduced ejection fraction (HFrEF) are driven by different pathomechanisms (blue and red arrows). While both share some degree of neurohumoral activation (middle), the proposed paradigm suggests systemic low-grade inflammation and oxidative stress are more prominent mediators of HFrEF, whereas cardiomyocyte injury is pivotal in HFrEF. Downstream signaling activates some protective (green circular arrow) but overwhelmingly maladaptive (red circular arrows) pathways (5). LV hypertrophic remodeling is common but not inevitable (thin arrows); however, the cellular phenotype differs in HFrEF vs HFrEF. See text for more details. COPD, chronic obstructive pulmonary disease; ROS, reactive oxygen species.](japplphysiol.00374.2015/Fig1.jpg)
type. Loss of contractile function within the remaining cardiomyocytes during LV remodeling promotes the transition from LVH to HFrEF. On the other hand, in HFrEF, cardiomyocyte and extracellular matrix passive stiffness are increased (Fig. 1, and see section, CELLULAR MECHANISMS OF CONTRACTILE DYSFUNCTION FOR TREATMENT OF HFrEF). Triggers of LVH often also activate cardioprotective signaling in cardiomyocytes (e.g., as triggered by natriuretic peptides); however, the maladaptive pathways prevail during the natural course of the disease (see Ref. 5 for a more detailed review).

MYOCARDIAL DYSFUNCTION ASSOCIATED WITH PATHOLOGICAL LVH

The link between maladaptive LVH and diastolic dysfunction was established more than 30 years ago (see Ref. 72 for review). ECG signs of LVH are a strong predictor of diastolic dysfunction (61). In fact, in HFrEF, LVH is the most frequent structural cardiac abnormality. Arterial hypertension is common as a trigger of LVH and present in the majority of HFrEF patients (Table 1). In HFrEF patients, LVH is correlated with hospitalization for heart failure, cardiovascular death, and aborted cardiac arrest (37, 106), underscoring the role of LVH as a prognostic marker. However, underlying pathomechanisms that may link LVH to diastolic dysfunction and HFrEF are still not completely understood. Functional effects of LVH have been extensively studied in hypertrophic cardiomyopathy. In these conditions, global LV systolic function [ejection fraction (EF), LV emptying] is initially augmented, indicating a hypercontractile state (13). HFrEF patients reportedly have more pronounced concentric hypertrophy than patients with hypertensive heart disease without HFrEF (80). HFrEF is an exercise-related syndrome, and LVH correlates with an attenuated increase or even decrease in LV EF (LVEF) during exercise and reduced exercise capacity (81), depending on LVH etiology (104). Patients with a concentric type of LVH performed worst during exercise, attributed to reduced contractile reserve, but also to chronotropic incompetence (63). Lam et al. found a significant, albeit weak, inverse correlation between LVH and exercise capacity (63). Notably, when further adjusting for known confounders, such as age, sex, clinical variables, comorbidities, and medication, the association of exercise capacity and LVH was markedly attenuated or no longer detectable (19).

ALTERED REGIONAL CONTRACTILITY IN LVH AND HFrEF

Previous studies have suggested that patients with LVH and preserved EF may have subtle systolic dysfunction not reflected by the EF (7, 95). In recent years, LV deformation during systole has been quantified in multiple planes using speckle tracking echocardiography or MRI tissue tagging. Planes of deformation have been defined related to myocardial fiber orientation, including longitudinal, radial, and circumferential shortening (strain) (108). As reported earlier in this journal (99) and confirmed in other conditions of hypertrophic cardiac remodeling, an increase in radial strain may conceal loss of contractile function along the longitudinal heart axis (longitudinal strain) thus maintaining a preserved global EF (58, 60). Deterioration of regional strain correlates with regional myocardial hypertrophy (127) and parallels increased LVH in rodents (57), in pigs (115), as well as in patients (120). Regional contractile dysfunction is potentially related to increased regional fibrosis (120). In the PARAMOUNT trial, impaired longitudinal strain in HFrEF patients was not correlated to other markers of diastolic dysfunction, but associated with N-terminal prohormones of brain natriuretic peptide, which was interpreted as a sign of systolic dysfunction, despite preserved EF (60). However, others found a reduction in global longitudinal strain in hypertensive patients to be strongly associated with diastolic dysfunction, but not with LVH (28). Notably, a decrease in longitudinal and increase in radial regional strain in response to myocardial stress is a common pattern and has been observed early (i.e., before the onset of global diastolic dysfunction) as recently confirmed in a large-animal model (41) and in patients (86). Impaired regional strain may even occur before LVH manifestation (25). The increase in radial strain may dissipate during the progression of LVH (58). In HFrEF, LVH is associated with a higher degree of spatial heterogeneity in longitudinal strain at rest (100) and even more pronounced dysynchrony in regional contraction during exercise (113). In hypertrophic cardiomyopathy, such regional functional heterogeneity was associated with the distribution of myocardial fibrosis (9). Increased fibrosis has recently been related to the deterioration of regional strain also in a large-animal model of hypertensive heart disease (115). It has to be kept in mind that LV relaxation is also a function of LV afterload (ventricular-arterial coupling, see Ref. 49 for review). For instance, LV relaxation was more prolonged in hypertensive HFrEF patients than nonhypertensive HFrEF patients related to altered LV-arterial coupling (27). In analogy, changes in regional strain in response to exercise may also respond to exercise-induced alterations in afterload, which differ, depending on LVH etiology (104).

In summary, LVH is associated with global diastolic dysfunction and HFrEF in experimental and clinical studies, which is the basis for the inclusion of LVH as a diagnostic marker in the clinical algorithm to detect HFrEF (90). Structural remodeling induces regions of reduced regional strain

<table>
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<th>Study Acronym</th>
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<th>LVH, %</th>
<th>Reference No.</th>
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<td>98</td>
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<td>92</td>
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N, no. of subject, LVH, left ventricular hypertrophy; RELAX, phosphodiesterase-5 inhibition to improve clinical status and exercise capacity in diastolic heart failure; TOPCAT, treatment of preserved cardiac function heart failure with an aldosterone antagonist; CHARM-ES, candesartan in heart failure: assessment of reduction in mortality and morbidity-preserved echocardiographic substudy; PARAMOUNT, prospective comparison of ARNI with ARB on management of heart failure with preserved ejection fraction; I-PRESERVE, irbesartan in heart failure with preserved ejection fraction study; Aldo-DHF, aldosterone receptor blockade in diastolic heart failure. n.a., Not available. *Mean left ventricular mass index was 83±25 g/m² (men; normal reference range 49–115 g/m²; Ref. 64) and 77±20 g/m² (women; normal reference range 43–95 g/m²) in I-PRESERVE (30) and 109±28 g/m² in Aldo-DHF (20).
during systole that are compensated by areas of increased contractile function, and this heterogeneity may contribute to diastolic dysfunction and exercise limitation, with and without LVH.

**CELLULAR MECHANISMS OF CONTRACTILE DYSFUNCTION IN LVH AND HFpEF**

Altered contractility in LVH at the organ level is related to structural and functional abnormalities involving the extracellular matrix and fibrous tissue, the vasculature, as well as the cardiomyocytes themselves. See Fig. 2.

LVH is often associated with increased fibrosis, mostly reactive interstitial fibrosis, even though replacement fibrosis following cardiomyocyte apoptosis has also been described (29). An increase in total collagen expression and cross-linking was associated with diastolic dysfunction and HFpEF (48). In chronic kidney disease and in diabetic cardiomyopathy, LV fibrosis and diastolic dysfunction are not necessarily linked to the presence of LVH (24, 75), but fibrosis may promote the progression of LVH to heart failure (23).

LVH, as well as other risk factors, such as age, diabetes, obesity, and hypertension, which are associated with HFpEF, have been linked to coronary microvascular rarefaction in animal models and patients (43, 116). Vice versa, reversal of myocardial hypertrophy (121) or vascular endothelial growth factor gene therapy (105) in murine models of HFpEF increased microvascular density, along with improvement of diastolic function. In mouse models, microvascular rarefaction preceded LVH, suggesting that microvascular dysfunction may also be a cause of diastolic dysfunction, independent of LVH (93). On the other hand, in a pig model of HFpEF (aortic banding), capillary density was unchanged in hypertrophied hearts (21). A recent study in human autopsies supported a link between microvascular rarefaction and HFpEF in a cohort with high prevalence (65%) of coronary artery disease (82). In summary, while microvascular dysfunction and vascular remodeling during LVH may promote HFpEF, the role of microvascular rarefaction in human HFpEF with different leading comorbidities remains to be determined. It has also been postulated that vascular dysfunction, altered extracellular matrix composition, and cytokines modulate cardiomyocyte function in HFpEF (89).

Cardiomyocyte contractile function is controlled by Ca\(^{2+}\)-dependent myofilament activation and relaxation, as well as by passive viscoelastic properties largely determined by the myofilaments (e.g., titin-related stiffness). As in the whole organ, mechanical energy stored in the sarcomeric protein titin during contraction contributes to recoil during relaxation. Vice versa, resting cardiomyocyte tension in diastole is a determinant of contractile force during systole. Thus the relationship between “systolic” and “diastolic” function at the cellular level is expected to be highly interdependent.

Following seminal studies of Paulus’ group (6, 122), who reported significantly increased resting tension in cardiomyocytes from patients with HFpEF correlating with end-diastolic pressure in vivo, increased cardiomyocyte passive stiffness has been confirmed in several animal models with LVH and diastolic dysfunction (36, 45). The large sarcomeric protein titin acts as a molecular spring and is a main determinant of passive stiffness (68). Interestingly, titin-dependent stiffness is increased in patients with arterial hypertension and HFpEF, but not in patients with hypertension alone (128), supporting its mechanistic role. As titin-associated proteins also may be involved in mechanosensing and hypertrophic signaling, it is currently unclear whether altered titin function is the cause or effect of LV hypertrophic remodeling (62). In addition, hypophosphorylation of myofilaments, leading to increased Ca\(^{2+}\) sensitivity, may also contribute to impaired cardiomyocyte relaxation in HFpEF (35).

Due to the limited availability of myocardial samples that would allow isolation of functional cardiomyocytes, active cardiomyocyte contraction has not been studied in human HFpEF. In LVH in the absence of ischemia, an increase in cardiomyocyte size is achieved by the addition of sarcomeres in parallel in concentric hypertrophy or sequentially (longitudinally) in eccentric hypertrophy (102). Experimental evidence suggests that, also at the cellular level, hypertrophy is associated with altered contractile function. Studies in several animal models with LVH (e.g., aortic stenosis, hypertension, diabetes, or kidney dysfunction) have demonstrated impaired active cardiomyocyte relaxation (26, 73, 78). Cardiomyocytes from animals models with hypertrophied, nonfailing hearts show cytosolic Ca\(^{2+}\) transients with normal or increased amplitude, often with slowed Ca\(^{2+}\) decay during diastole and increased diastolic intracellular Ca\(^{2+}\) concentration ([Ca\(^{2+}\)]), indicating increased cytosolic Ca\(^{2+}\) load, which may contribute to slowed cardiomyocyte relaxation and promote remodeling (77, 84). However, most small-animal models of LVH with signs of

![Fig. 2. Cellular pathomechanisms linking LV hypertrophy to diastolic dysfunction. See text for details. ECM, extracellular matrix.](https://www.jappl.org)
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Fig. 3. Top right: example of intracellular Ca\textsuperscript{2+} concentration transients from healthy (N = 3) and remodeled hearts (N = 2, ejection fraction 45%; 1 with concentric remodeling and 1 with eccentric hypertrophy). Ca\textsuperscript{2+} transient amplitude (top left) was significantly increased. Changes in time to half maximal release (TF50; bottom right) and relaxation (RT50; bottom left) did not reach significance (nos. under bars indicate no. of cells, error bars = SE). F/F\textsubscript{0}, fluorescence ratio; F\textsubscript{peak}, peak fluorescence.

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The multifactorial origin of diastolic dysfunction in clinical settings may also explain the weaker association between LVH regression and improvement of diastolic function. In the RELAX trial, the presence of LVH did not affect treatment efficacy with sildenafil (98), indicating that a better understanding of the cellular mechanisms linking LVH to HFpEF is warranted to refine therapeutic approaches.

Hypertrophic remodeling is, in part, counterbalanced by anti-hypertrophic pathways, including cyclic guanosine monophosphate (cGMP)-dependent signaling triggered by nitric oxide or natriuretic peptides (5). HFpEF has been linked to reduced cGMP-mediated signaling, and, in experimental conditions, increasing cGMP by inhibition of phosphodiesterase 5 (PDE5, by sildenafil) attenuated LVH and diastolic dysfunction (85). Surprisingly, sildenafil failed to improve diastolic dysfunction or LVH in the RELAX trial (98), questioning PDE5 as a therapeutic target at least in an unselected cohort of patients with HFpEF.
EXERCISE EFFECTS ON LVH AND HFpEF

Disturbed diastolic function and increased vascular stiffness are major contributors to exercise limitation in patients with HFpEF (10, 39, 53). The subsequent rise in LV filling pressure at rest and/or during exercise has been suggested to be directly related to the severity of HF symptoms in HFpEF patients.

Several single center trials addressed the role of exercise training on exercise capacity and cardiac function in patients with HFpEF. Although they demonstrated a significant improvement of exercise capacity and quality of life, they failed to demonstrate an improvement of cardiac systolic or diastolic function or of LVH (40, 52, 114). Similar findings were made under more controlled conditions in a translational large animal model of HFpEF (74). In a prospective clinical approach, the multicenter Exercise Training in Diastolic Heart Failure Pilot study (Ex-DHF-P) randomized patients with New York Heart Association class II-III, LVEF ≥ 50%, echocardiographic evidence of diastolic dysfunction, sinus rhythm, and ≥1 additional cardiovascular risk factor to 32 sessions of supervised, combined endurance/resistance exercise training (n = 44) or to usual care (n = 20) (18). Peak oxygen consumption after 3 mo (primary endpoint) significantly improved with training, resulting in a between-group difference of 3.3 ml·kg⁻¹·min⁻¹ (P < 0.001). Also, the resting LV filling index (E/e′), the left atrial volume index, and different quality of life dimensions were improved after follow-up (87). Again, as also reported in previous trials, LVH did not change after training.

Several reasons might contribute to the actual lack of evidence regarding the link between improved exercise capacity, improved cardiac diastolic function, and the regression of LVH. In all available studies, the intervention period was limited (12, 16, or 24 wk). Furthermore, patients were not classified using a comparable diagnostic algorithm as now recommended for the diagnosis of HFpEF (79, 90). Last, the induction of physiological adaption of the myocardium induced by exercise training might cover the beneficial effects of exercise training on detrimental cardiac remodeling processes in this HF population with preserved LVEF. Future studies are, therefore, urgently needed to further elaborate the effects of exercise training on cardiac structure and function. The ongoing Exercise Training in Diastolic Heart Failure (Ex-DHF) study will randomize n = 320 patients (1:1 ratio) to exercise training or usual care and will have an individual 12-mo follow-up (ISRCTN 86879094; http://www.controlled-trials.com). Since LVH is part of the specific inclusion criteria used in Ex-DHF, this study might help to better understand the effects of exercise training on LVH in this condition.

SUMMARY AND CONCLUSION

Experimental and clinical studies indicate that maladaptive LVH, i.e., in the presence of pathological stimuli, can per se induce diastolic dysfunction and thus contribute to the HFpEF phenotype. Mechanisms are diverse and probably etiology specific and include vascular dysfunction and potentially vascular rarefaction, changes in the extracellular matrix composition, including increased fibrosis, and alterations of the intrinsic active and passive contractile properties of the cardiac myocyte. In the multifactorial clinical setting of HFpEF, diastolic dysfunction and HFpEF are also observed in the absence and independent of LVH in a considerable number of patients. A reduction of LVH is not necessarily associated with an improvement of diastolic function. Thus current clinical evidence does not support regression of LVH as a surrogate marker for short-term improvement of HFpEF.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: F.R. Heinzl conception and design of research; F.R. Heinzl interpreted results of experiments; F.R. Heinzl, F.R. Hohendanner, and G.J. prepared figures; F.R. Heinzl, F.R. Hohendanner, and G.J. drafted manuscript; F.R. Heinzl, F.R. Hohendanner, S.S., and F.E. edited and revised manuscript; F.R. Heinzl, F.R. Hohendanner, G.J., S.S., and F.E. approved final version of manuscript; F.R. Hohendanner and S.S. analyzed data; G.J. and S.S. performed experiments.

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