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Influence of exercise training on left ventricular diastolic function and its relationship to exercise capacity in patients after myocardial infarction

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Abstract

Background: *The study's aim was to examine the effect of exercise training on left ventricular diastolic function (LVDF) and whether LVDF could predict an improvement in exercise capacity (EC) in post-myocardial infarction patients.*

Methods: *Forty-eight males, aged 56.4 ± 7.2 years, with preserved left ventricular systolic function (LVSF) and mild diastolic dysfunction (the ratio of transmitral early left ventricular filling velocity to early diastolic mitral annulus velocity E/E' > 8 as the average of the septal and lateral annulus velocities), were assigned to either a training group (TG, n = 32) or controls (n = 16). Before, and at the end of the study, all patients underwent a cardiopulmonary test and echocardiography with tissue Doppler imaging (TDI).*

Results: *After a 4.5-month training program, maximal oxygen consumption increased significantly in TG (26.66 ± 3.88* vs. *28.79 ± 5.00 mL/kg/min, p < 0.0001). TDI-derived E/E' did not change after the training program. After dividing TG according to septal E/E's > 10 and < 10 and lateral E/E'l > 8 and < 8, exercise capacity improved significantly only in patients with E/E's < 10 and E/E'l < 8.*

Conclusions: *A 4.5-month training program in post-myocardial infarction patients with preserved LVSF and mild diastolic dysfunction led to improved exercise capacity only in TG. The diastolic function did not change significantly. The improvement in exercise capacity was significantly greater in patients with a better LVDF measured by TDI.* (Cardiol J 2010; 17, 2: 136–142)

Key words: exercise training, left ventricular diastolic function, tissue Doppler imaging, exercise capacity

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Introduction

It is still unclear whether exercise training can improve diastolic cardiac function and whether the changes in resting diastolic function can predict an improvement in exercise capacity in patients after myocardial infarction.

To date, only a few studies have investigated the effect of exercise training on left ventricular diastolic function (LVDF) assessed exclusively by conventional echocardiographic imaging. For example, Yu et al. [1] examined the influence of exercise training on resting LVDF in coronary artery disease (CAD) patients with impaired diastolic and preserved systolic function. They showed that a training program prevented the progression of LVDF without affecting its systolic function. It is worth pointing out that the literature lacks data assessing the influence of exercise training on tissue Doppler imaging (TDI) derived parameters of the diastolic function. Therefore, the objective of our study was to assess the effect of exercise training on LVDF using conventional and TDI, and to find whether changes in resting diastolic cardiac function could predict an improvement in exercise capacity in patients with stable angina and after myocardial infarction.

Methods

Our study comprised 48 male patients, aged 56.4 ± 7.2 years, one month after myocardial infarction (MI) treated with primary percutaneous coronary intervention. Sixteen patients refused to participate and constituted a control group (CG). The patients (n = 32) who agreed to participate in the 4.5-month exercise training program and who met the entry criteria were assigned to a training group (TG). The inclusion criteria were as follows: stable angina before the study, age ≤ 65 years, preserved left ventricular systolic function (LVEF ≥ 50%) assessed by two-dimensional echocardiography (ECHO) and mild diastolic dysfunction assessed by TDI, which meant the ratio of transmitral early left ventricular filling velocity to early diastolic mitral annulus velocity (E/E') was > 8 as the average of the septal and lateral annulus velocities.

The study protocol was approved by the Institutional Ethics Committee, and informed written consent was obtained from each patient.

Cardiopulmonary exercise test

To determine the exercise capacity accurately, all patients underwent a symptom-limited cardiopulmonary exercise test (CPET) on a treadmill according to the modified Bruce protocol using Reynolds ZAN 600USB CPX.

The following variables were determined: maximal oxygen consumption (maxVO_2, mL/kg/min), exercise duration (ED, min), walking distance (WD, m), heart rate (HR, beats per minute — bpm), and blood pressure (BP, mm Hg) at rest and peak exercise.

Two-dimensional echocardiography

Imaging was done in the left lateral decubitus position using a VIVID 7 (General Electric) with a multifrequency transducer equipped with TDI software. Cardiac chamber dimensions were measured according to the recommendations of the American Society of Echocardiography and the European Association of Echocardiography [2].

Transmitral left ventricular filling velocities at the tips of the mitral valve leaflets were obtained from the apical four chamber view using pulsed wave Doppler echocardiography. The transmitral left ventricular filling signal was traced manually and the following variables derived: peak velocity of early (E, m/s) and late (A, m/s) filling, E wave deceleration time (DT, ms), and E/A ratio. Isovolumetric relaxation time (IVRT) was determined using continuous wave Doppler echocardiography in accordance with the standard methodology.

Left ventricular ejection fraction was obtained by Simpson's biplane method. Wall motion was scored according to a 16-segment model, in which one was considered normal or hyperdynamic, two was hypokinetic, three was akinetic, four was dyskinetic, and five was aneurismal [2, 3].

Tissue Doppler imaging

From the apical four chamber view, a 10 mm Doppler sample volume was placed at the lateral and septal margins of the mitral annulus. Tissue Doppler imaging velocities were recorded at a sweep speed of 100 mm/s and stored on S-VHS video tape for playback and analysis. All measurements were made in three cardiac cycles and averaged by an investigator.

The following measurements were made from the TDI recordings: early (E'), and late (A') diastolic velocities of lateral (E'l) and septal (E's) part of mitral annulus in m/s. The septal and lateral early diastolic velocities were measured separately and averaged: E'a, A'a. The ratios of E' to A' and E to E' were calculated [4].

Exercise training program

The training program lasted 4.5 months and consisted of two cycles of training: 16 interval ses-

Table 1. Baseline characteristics.

	Training group (n = 32)	Control group (n = 16)	p
Age	55.16 ± 7.7	58.88 ± 5.3	NS
Body mass index	27.86 ± 3.1	28.28 ± 32	NS
CCS Class 0	21 (65.6%)	8 (50%)	NS
CCS Class I	11 (34.4%)	8 (50%)	NS
Anterior myocardial infarction	16 (50%)	10 (62.5%)	NS
Inferior myocardial infarction	16 (50%)	6 (37.5%)	NS
Coronary stenosis < 50% in 3 vessels	26 (80.3%)	13 (83.3%)	NS
Coronary stenosis ≥ 50% in 1 vessel except that treated with PCI	6 (18.8%)	3 (18.8%)	NS
Left ventricular ejection fraction	59 ± 8.2	57.6 ± 10.4	NS
Wall motion score index	1.07 ± 0.1	1.1 ± 0.2	NS
Smoking history	15 (46.9%)	8 (50%)	NS
Hypertension	22 (68.8%)	9 (56.25%)	NS
Diabetes mellitus	3 (9.37%)	1 (6.25%)	NS
Hypercholesterolemia	32 (100%)	16 (100%)	NS
Medications:			
Beta-blockers	32 (100%)	16 (100%)	NS
ACEI	31 (96.9%)	16 (100%)	NS
Statins	32 (100%)	16 (100%)	NS
Antiplatelet agents:			
Aspirin	32 (100%)	16 (100%)	NS
Clopidogrel	32 (100%)	16 (100%)	NS

Data are expressed as mean ± SD or percentages; NS — non significant; CCS — classification of angina according to the Canadian Cardiovascular Society; PCI — percutaneous coronary intervention; ACEI — angiotensin-converting enzyme inhibitors

sions on a cycloergometer three times a week, followed by 24 sessions of gymnastics twice a week. Each session lasted 40 minutes. The limit for the training workload was set at 80% of maximal heart rate reached during CPET. The training in the gymnasium was a continuation of the interval training. It also lasted 40 minutes and consisted of general fitness exercises alternated with breathing exercises. The level of exercise intensity in the both training cycles was comparable because patients did their exercises until they reached 80% of the heart rate established during stress test. Interval training is a form of endurance training. The basic factor determining the endurance of the organism is exercise capacity defined as the maximal capability of oxygen consumption (maxVO_2). General fitness exercises, apart from improving exercise capacity, also improve general fitness, because during such training all muscle groups are activated.

Statistical analysis

Statistical analysis was performed using SAS statistical software (version 8.2, Cary NC, USA). All data was expressed as mean ± standard deviation. Student's t-test for matched pairs was used to compare the parameters of a continuous type in the two groups studied, when the distribution of variables did not differ significantly from the normal distribution. When it did so, a non-parametric rank test was used. In order to assess the differences of categorized parameters in the two groups χ^2 test was used when the number was high enough, or Fisher's exact test when it was not. The association between parameters was assessed with the monofactorial generalized linear model. A p value < 0.05 was considered statistically significant.

Results

The baseline characteristics of the study population are listed in Table 1. There were no significant differences between training and control patients with regard to baseline clinical variables and therapy. Table 2 shows CPET results obtained before, and at the end of, the study. At baseline, no significant differences in exercise capacity were observed between the two groups; only systolic BP at rest ($p < 0.01$), systolic BP at peak ($p < 0.01$) and diastolic BP at peak ($p = 0.05$) was higher in the CG. After completion of the training program (TP) maxVO_2 increased significantly only in the TG patients, confirming that only an appropriately

Table 2. Cardiopulmonary exercise testing results in both study groups before (I) and at the end (II) of the study.

	Training group (n = 32)		p	Control group (n = 16)		p
	I	II		I	II	
VO_2max [mL/kg/min]	26.66 ± 3.88	28.79 ± 5.00	< 0.0001	26.23 ± 4.28	26.34 ± 3.85	NS
Duration [min]	12.39 ± 1.70	14.12 ± 1.35	< 0.0001	13.30 ± 1.20	13.65 ± 1.61	NS
Walking distance [m]	681.00 ± 130.31	821.61 ± 130.05	< 0.0001	764.00 ± 124.05	778.31 ± 149.81	NS
HR at rest [bpm]	68.11 ± 9.17	70.68 ± 11.49	NS	68.78 ± 11.27	62.78 ± 11.49	NS
SBP at rest [mm Hg]	114.47 ± 12.57	122.63 ± 12.4	NS	130 ± 10.31	130 ± 12.25	NS
DBP at rest [mm Hg]	75.26 ± 5.65	82.11 ± 7.87	< 0.0003	78.89 ± 6.01	77.22 ± 5.65	NS
HR at peak [bpm]	127 ± 13.88	133.32 ± 12.48	< 0.02	118.22 ± 15.23	127.89 ± 14.87	< 0.03
SBP at peak [mm Hg]	159.21 ± 19.02	175.00 ± 21.08	< 0.004	190.00 ± 25.98	185.56 ± 30.15	NS
DBP at peak [mm Hg]	84.74 ± 6.97	90.53 ± 11.77	NS	92.22 ± 10.03	89.44 ± 8.82	NS

All values are presented as mean ±SD; NS — non significant; there were no intergroup differences in baseline values for these variables in both study groups; VO_2max — maximal oxygen consumption; HR — heart rate; SBP — systolic blood pressure; DBP — diastolic blood pressure

Table 3. Tissue Doppler indices of left ventricular function before (I) and at the end (II) of the study.

	Training group (n = 32)		p	Control group (n = 16)		p
	I	II		I	II	
E'l	0.09 ± 0.02	0.09 ± 0.02	NS	0.08 ± 0.02	0.09 ± 0.02	NS
A'l	0.10 ± 0.02	0.10 ± 0.2	NS	0.10 ± 0.03	0.10 ± 0.2	NS
E'/A'l	1.02 ± 0.48	0.99 ± 0.48	NS	0.99 ± 0.58	0.87 ± 0.27	NS
E/E'l	7.52 ± 3.25	7.54 ± 2.62	NS	9.14 ± 3.82	8.44 ± 3.9	NS
E's	0.09 ± 0.09	0.07 ± 0.01	NS	0.06 ± 0.01	0.07 ± 0.02	NS
A's	0.10 ± 0.02	0.10 ± 0.02	NS	0.10 ± 0.02	0.10 ± 0.01	NS
E'/A's	0.93 ± 1.09	0.69 ± 0.20	NS	0.62 ± 0.11	0.67 ± 0.19	NS
E/E's	9.22 ± 3.5	9.90 ± 3.1	NS	11.52 ± 4.12	11.41 ± 5.1	NS
E'a	0.09 ± 0.04	0.08 ± 0.01	NS	0.07 ± 0.01	0.08 ± 0.02	NS
A'a	0.10 ± 0.02	0.10 ± 0.02	NS	0.10 ± 0.02	0.10 ± 0.01	NS
E'/A'a	0.99 ± 0.6	0.86 ± 0.31	NS	0.76 ± 0.35	0.77 ± 0.22	NS
E/E'a	8.41 ± 2.97	8.67 ± 2.66	NS	10.69 ± 3.86	10.38 ± 4.63	NS

All values are presented as mean ±SD; NS — non significant; there were no intergroup differences in baseline values for these variables in both study groups; E — early transmitral left ventricular filling velocity [m/s]; E' — early diastolic mitral annulus velocity [m/s]; A' — late diastolic mitral annulus velocity [m/s]; l — lateral, s — septal, a — average

planned TP can favorably change exercise capacity. In conventional Doppler measurements, only DT was significantly shorter in TG patients after TP (232.25 ± 57.5 *vs*. 205.07 ± 56.6, p = 0.01). Table 3 represents TDI indices of left ventricular function in both study groups. There were no significant changes in values of E/E' and E'/A' of all studied parts of the mitral annulus after TP. But, when we divided trained patients according to the septal E/E's ratio into two subgroups (> 10 and < 10) we found a significant improvement of physical capacity after TP only in patients with the E/E's ratio < 10 (Table 4).

Moreover, when we divided trained patients according to the lateral E/E' ratio into two subgroups (> 8 and < 8) we found a marked improvement of physical capacity only in the subgroup with the E/E'l ratio < 8 (Table 5). There were no significant differences between the subgroups of patients with high and low E/E' in demographic characteristics, physical capacity at entry and after training. We also assessed the relationship between some parameters from CPET and ECHO. There was a negative correlation between the E/E' a ratio and maxVO_2 (r = = –0.587, p < 0.05), duration (r = –0.571, p < 0.05) and WD (r = –0.615, p < 0.03) after TP.

Table 4. Exercise testing results in trained patients divided according to the septal E/E's ratio > 10 and < 10 before (I) and after (II) the training program.

	E/E's > 10 (n = 14)		p	E/E's < 10 (n = 18)		p
	I	II		I	II	
VO_2max [mL/kg/min]	27.7 ± 4.43	29.33 ± 5.93	NS	26.69 ± 4.44	28.38 ± 4.34	< 0.03
Duration [min]	13.87 ± 1.44	14.08 ± 1.55	NS	13.5 ± 1.48	14.56 ± 1.24	< 0.004
Walking distance [m]	789.42 ± 135.89	816.17 ± 148.13	NS	768.88 ± 140.89	825.69 ± 119.64	< 0.005
HR at rest [bpm]	62.42 ± 10.29	66.33 ± 12.2	NS	71.98 ± 8.01	69.5 ± 10.8	NS
SBP at rest [mm Hg]	124.58 ± 11.96	130 ± 13.31	NS	116.56 ± 10.28	121.25 ± 11.03	NS
DBP at rest [mm Hg]	78.33 ± 6.85	82.5 ± 8.66	NS	76.56 ± 5.39	79.06 ± 6.38	NS
HR at peak [bpm]	121.5 ± 12.38	127.33 ± 11.07	0.02	132.44 ± 15.08	134.75 ± 14.2	NS
SBP at peak [mm Hg]	173.2 ± 31.33	176.25 ± 21.40	NS	173.75 ± 22.77	180 ± 126.83	NS
DBP at peak [mm Hg]	87.50 ± 11.58	89.17 ± 8.21	NS	87.19 ± 9.3	90.94 ± 12.55	NS

All values are presented as mean ±SD; NS — non significant; VO_2max — maximal oxygen consumption; HR — heart rate; SBP — systolic blood pressure; DBP — diastolic blood pressure; E — transmitral early left ventricular filling velocity [m/s]; E's — early diastolic septal part of mitral annulus velocity [m/s]

Table 5. Exercise testing results in trained patients divided according to the lateral E/E'l ratio > 8 and < 8 before (I) and after (II) the training program.

	E/E'l > 8 (n = 10)		p	E/E'l < 8 (n = 22)		p
	I	II		I	II	
VO_2max [mL/kg/min]	27 ± 4.2	29.69 ± 6.75	NS	26.54 ± 3.88	28.49 ± 4.44	< 0.0002
Duration [min]	11.85 ± 2.91	13.57 ± 1.39	NS	12.57 ± 1.12	14.31 ± 1.32	< 0.0001
Walking distance [m]	663.14 ± 220.33	769.43 ± 127.29	NS	685.95 ± 90.61	839 ± 129.36	< 0.0001
HR at rest [bpm]	69.71 ± 14.4	66.43 ± 13.5	NS	67.86 ± 7.97	68.71 ± 10.7	NS
SBP at rest [mm Hg]	125 ± 10.44	130 ± 17.8	NS	117.62 ± 14.5	123.33 ± 10.76	NS
DBP at rest [mm Hg]	79.29 ± 1.89	78.57 ± 6.27	NS	75.48 ± 6.5	81.19 ± 7.89	< 0.02
HR at peak [bpm]	124.71 ± 16.17	126.29 ± 12.85	NS	124 ± 14.53	133.33 ± 13.23	< 0.0001
SBP at peak [mm Hg]	185.71 ± 22.25	183.57 ± 24.62	NS	163.57 ± 24	176.67 ± 24.56	< 0.01
DBP at peak [mm Hg]	88.57 ± 9.45	88.57 ± 9	NS	86.67 ± 8.56	90.71 ± 11.43	NS

All values are presented as mean ±SD; NS — non significant; VO_2max — maximal oxygen consumption; HR — heart rate; SBP — systolic blood pressure; DBP — diastolic blood pressure; E — transmitral early left ventricular filling velocity [m/s]; E'l — early diastolic lateral part of mitral annulus velocity [m/s]

Discussion

We found that a 4.5-month training program in stable, optimally treated post-MI patients with preserved left ventricular systolic function and with mild diastolic dysfunction (in TDI the average E/E'a ratio > 8), led to a significant improvement in physical capacity only in trained patients.

To clarify the impact of exercise training on LVDF, we investigated conventional Doppler as well as TDI indexes of diastolic function. We showed that our TP resulted only in significant shortening of DT, whereas the remaining conventional Doppler indices i.e. E, A, E/A and IVRT did not change in either study group.

To date, there have been few articles assessing the influence of exercise training on the left ventricular diastolic function using conventional Doppler imaging.

Yu et al. [1] trained 127 patients after MI with moderate diastolic dysfunction of left ventricle for eight weeks and observed a significant increase of E, E/A, and shortening of DT as well as IVRT.

In contrast, Gates et al. [5] found that aerobic endurance exercise did not modulate consistently the changes in the left ventricular diastolic function that occur with physiological aging in healthy men.

Tissue Doppler imaging is a relatively new ECHO modality for measuring myocardial velocity. Mitral annulus velocity measured by TDI has

shown to be a preload-independent marker for assessment of LVDF [6–8]. Especially, the ratio of early mitral valve flow velocity to early diastolic velocity of mitral annulus (E/E') is considered to be a sensitive, noninvasive index of LVDF and showed a better correlation with the left ventricular diastolic pressure than did other Doppler variables. Recently, Paulus et al. [4] proposed to use the mean value of the annular velocities from the septum and the lateral wall, and noted that average E/E' ratio < 8 (E/E'a) predicted normal LVDF.

Moreover, Arques et al. [9] suggested that the septal part of mitral annulus velocity had a slightly better correlation with mean left ventricular diastolic pressure than that of the lateral part, and the E/E's ratio > 10 predicted abnormal diastolic function.

In our study there were no significant changes in mean TDI values of the E', A', E/E' and E'/A' ratios of all parts of the mitral annulus in either study group. Therefore, we used recommended cut-off values of the average E/E' ratio to identify more precisely patients with abnormal LVDF and to examine the influence of left ventricular diastolic performance on exercise capacity. After dividing TG according to septal E/E's > 10 and < 10 and lateral E/E'l > 8 and < 8, exercise capacity improved significantly only in patients with E/E's < 10 and E/E'l < 8.

These results may emphasize the role of the diastolic function as an important determinant of exercise tolerance improvement.

Recently, Skaluba and Litwin [10] analyzed 121 patients with suspected CAD and normal ejection fraction referred for exercise training. They found that E/E's ratio > 10 was the strongest independent predictor of reduced exercise tolerance. Also Van de Veire et al. [11] showed that maxVO_2 was independently predicted by an E/E's ratio.

Findings confirming the above were reported by Burgess et al. [12] in a large patient population with preserved left ventricular systolic function; the exercise capacity was significantly smaller in patients with mild diastolic dysfunction and abnormal E/E's ratio > 10.

In our study, we also assessed the relationship between changes in the E/E'a ratio and maxVO_2, duration and walking distance after TP, and found a negative correlation between these variables. Hadano et al. [13] studied patients with heart failure, and stated that peak VO_2 correlated with E' and the E/E' ratio recorded from the lateral part of mitral annulus. Moreover, Kim et al. [14] studied patients with hypertension to identify determinants of exercise capacity and noted that early diastolic mitral annulus velocity (E'l) positively correlated with the duration of exercise stress test.

These findings may also confirm that an increase in physical capacity after training is greater in patients with a better diastolic function.

The mechanism by which the baseline LVDF contributes to exercise tolerance is not clear. It is well known that major factors limiting maxVO_2 are stroke volume and heart rate response to exercise [1, 11, 15]. We can only hypothesize that in our patients with preserved left ventricular systolic function, their exercise training improved the stroke volume response to exercise only in those without any abnormalities in the diastolic function. Moreover, it is possible that only in those patients did exercise training favorably alter the dilating capacity of their peripheral arteries, leading to an improvement in muscle function.

Thus, aerobic training in CAD patients without any abnormalities in diastolic function may facilitate an increase in the ability of the cardiovascular system to deliver oxygen to exercising skeletal muscles, leading to an improvement in physical work capacity, which can be clinically measured by oxygen uptake.

Conclusions

A 4.5-month TP in post-MI patients with preserved left ventricular systolic function and mild diastolic dysfunction led to improved physical capacity only in trained patients. The diastolic function did not change significantly after TP. The improvement in physical capacity after exercise training was significantly greater in patients with a better diastolic left ventricular function. The results we obtained suggest that diastolic left ventricular function may be an important determinant of exercise tolerance improvement after cardiac rehabilitation.

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References

1. Yu CM, Li LS, Lam MF, Siu DC, Miu RK, Lau CP. Effect of cardiac rehabilitation program on left ventricular diastolic function and its relationship to exercise capacity in patients with coronary heart disease: experience from a randomised controlled study. Am Heart J, 2004; 147: 11–18.

2. Lang RM, Bierig M, Devereux RB et al. Recommendations for chamber quantification. Eur J Echocard, 2006; 7: 79–108.
3. Mulvagh S, Quinones MA, Kleiman NS, Cheirif J, Zoghbi WA. Estimation of left ventricular end-diastolic pressure from Doppler transmitral flow velocity in cardiac patients independent of systolic performance. J Am Coll Cardiol, 1992; 20: 112–119.
4. Paulus WJ, Tschöpe C, Sanderson JE et al. How to diagnose diastolic heart failure: A consensus statement on the diagnosis of heart failure with normal left ventricular ejection fraction by the Heart Failure and Echocardiography Association of the European Society of Cardiology. Eur Heart J, 2007; 28: 2539–2550.
5. Gates PE, Tanaka H, Graves J, Seals DR. Left ventricular structure and diastolic function with human ageing. Relation to habitual exercise and arterial stiffness. Eur Heart J, 2003; 24: 2213–2220.
6. Nagueh SF, Middleton KJ, Kopelen HA, Zoghbi WA, Quinones MA. Doppler tissue imaging: A noninvasive technique for evaluation of left ventricular relaxation and filling pressures. J Am Coll Cardiol, 1997; 30: 1527–1533.
7. Pan C, Hoffmann R, Kuhl H, Severin E, Franke A, Hanrath P. Tissue tracking allows rapid and accurate visual evaluation of left ventricular function. Eur J Echocard, 2001; 2: 197–202.
8. Sohn DW, Chai IH, Lee DJ et al. Assessment of mitral annulus velocity by Doppler tissue imaging in the evaluation of left ventricular diastolic function. J Am Coll Cardiol, 1997; 30: 474––480.
9. Arques S, Roux E, Luccioni R. Current clinical applications of spectral tissue Doppler echocardiography (E/E' ratio) as a noninvasive surrogate for left ventricular diastolic pressures in the diagnosis of heart failure with preserved left ventricular systolic function. Cardiovasc Ultrasound, 2007; 5: 16.
10. Skaluba SJ, Litwin SE. Mechanism of exercise intolerance: Insight from tissue Doppler imaging. Circulation, 2004; 109: 972–977.
11. Van de Veire NR, De Winter O., Philippé J et al. Maximum oxygen uptake at peak exercise in elderly patients with coronary artery disease and preserved left ventricular function: The role of inflammation on top of tissue Doppler-derived systolic and diastolic function. Am Heart J, 2006; 152: 297.e1–297.e7.
12. Burgess MI, Jenkins C, Sharman JE, Harwik TH. Diastolic stress echocardiography: hemodynamic validation and clinical significance of estimation of ventricular filling pressure with exercise. J Am Coll Cardiol, 2006; 47: 1891–1900.
13. Hadano Y, Murata K, Yamamoto T et al. Usefulness of mitral annular velocity in predicting exercise tolerance in patients with impaired left ventricular systolic function. Am J Cardiol, 2006; 97: 1025–1028.
14. Kim HK, Kim YJ, Cho YS et al. Determinants of exercise capacity in hypertensive patients: New insights from Tissue Doppler Echocardiography. Am J Hypertens, 2003; 16: 564–569.
15. Grewal J, McCully RB, Kane GC, Lam C, Pellikka P. Left ventricular function and exercise capacity. JAMA, 2009; 3: 286–294.