Research Article

Evaluation of an MR-conditional "cardio stepper" for cardiopulmonary exercise testing

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Abstract

Background: Cardiovascular magnetic resonance imaging (CMR) represents the gold standard for routine examination of cardiac function and structure evaluation at rest and during exercise as well. Conventional stress CMR includes drug administration to increase heart rate (HR). The recently developed MR-conditional cardio stepper (CS) could be an alternative for real time stress CMR. So far, no data on cardiorespiratory responses exist for this device. Thus, this study evaluated cardiorespiratory responses to exhaustive testing on the CS compared to cycle and treadmill ergometry.

Methods: Forty-six healthy participants (24 men, 22 women, age: 31.4 ± 8.9 yrs, height: 174.8 ± 7.2 cm, weight: 70.3 ± 9.4 kg) performed three incremental exercise tests to volitional failure in a randomized crossover trial.

Results: Maximal values using the CS were significantly lower when compared to cycle and treadmill ergometry (HR_{max}: 170 ± 13 *vs.* 186 ± 9 *vs.* 190 ± 11 bpm, respectively; $p<0.05$, maximal oxygen uptake: 2971 ± 772 *vs.* 3531 ± 1023 *vs.* 3849 ± 1013 ml/min, respectively; $p<0.05$ and exercise duration: 539 ± 130 *vs.* 745 ± 157 *vs.* 710 ± 128 sec, respectively; $p<0.05$).

Conclusions: Although cardiorespiratory responses are not maximal when using the CS, the target heart rate, i.e. $>85\%$ of HR_{max}, for a stress CMR can be achieved.

Background

Cardiovascular magnetic resonance imaging (CMR) is used as a routine examination of cardiac function and structure evaluation [1], especially for coronary heart disease (CHD) diagnostics [2]. At rest, several perfusion defects of the heart, like coronary stenosis, remain undetected, especially in patients with unstable angina [3]. Therefore, stress tests during a CMR with a target heart rate of 85% of the theoretical maximal heart rate (220-age ± 10 bpm) are considered to be necessary [3-5]. To achieve this target heart rate, stress CMR is often carried out with drugs like Dobutamine and Adenosine [2,6]. However, this invasive procedure is associated with a potential risk of side effects like angina pectoris, hypertension, and even myocardial infarction etc. [6]. Considering these risks, alternative methods should be preferred. So far, several devices like treadmills, cycle ergometers and steppers for physical stress CMR were developed. Stress CMR on treadmills and upright cycle ergometers carried out outside the magnetic resonance tomograph (MRT) have the disadvantage of their inability to acquire cardiac images within 20 to 90 seconds of cessation of physical exercise, since this time is needed to get the post-stress image acquisition [7-9]. Consequently, post stress image acquisition at peak heart rate is not possible because of the exponentially decreasing heart rate after strenuous exercise [10]. To reduce time from finishing the stress test to post-stress imaging Lode developed a supine ergometer pedal (MRI Ergometer Pedal, Lode) for use during stress CMR. However, experiences in clinical settings show that performing supine cycle ergometer tests on the MRI Ergometer Pedal, with the goal of inducing high cardiac outputs, are not practicable due to the limited space in the MRT.

To overcome this limitation a short crank length of 60 mm was used to realize a real-time stress CMR [1]. However, according to Too and Landwer [11] and Martin and Spirduso [12] the optimal cycle crank length should be between 145 mm and 170 mm. Short cycle crank lengths result in a lower maximal power output, which might be insufficient to generate the needed heart rate increase for a stress CMR. Another commercially available device of Lode (MRI Ergometer Push/Pull, Lode) shows the same limitation with a maximum workload of 100 W. Using these devices, it is unlikely to reach the target heart rate of 85% of the theoretical maximal heart rate, which is necessary for a meaningful stress CMR [3-5]. This becomes particularly relevant for younger and trained subjects.

The cardio stepper (CS) developed by "Ergospect" (www.ergospect. com) generates the resistance via a hydraulic systems and allows a greater amplitude in the MRT due to step movements. This is of great advantage when compared to the above mentioned devices, because a clearly higher maximal power output and related maximal HR can be expected. However, until today no study exists that collected and compared cardiopulmonary standard values of maximal exercise testing on the CS with those of a standard treadmill or cycle ergometer.

Exercise tests using a cycle ergometer or a treadmill are among the most common tools for assessing the potential for and severity of CHD [13,14]. Furthermore, cardiorespiratory fitness testing is generally performed on these devices [15]. However, maximal cardiorespiratory responses attained on the cycle ergometer are somewhat lower compared with maximal treadmill values [16-18]. Smaller muscle involvement and greater regional muscle fatigue are thought to be responsible for this difference [19,20]. Such effects might also be expected for exercise testing with the CS. Additionally, it could be argued that the lack of familiarity with the CS exercise might lead to even lower values when compared to the cycle ergometer [21].

Therefore, the main goals of the current study were to evaluate if the target heart rate of 85% of the theoretical maximal heart rate can be achieved on the CS and to compare the maximal cardiorespiratory responses of the CS with those obtained by bicycle and treadmill testing. On the one hand we hypothesized that the target heart rate of 85% of the theoretical maximal heart rate will be reached using the CS but on the other hand we expected lower cardiopulmonary response achieved on the CS when compared to cycle and treadmill ergometry.

Methods

Subjects

A group of 46 healthy volunteers (24 men, 22 women, age: 31.4 ± 8.9 yrs, height: 174.8 ± 7.2 cm, weight: 70.3 ± 9.4 kg) were informed about the study aims and procedures and gave written informed consent to participate in the study. Volunteers completed a health history questionnaire to estimate potential risks associated with maximal exercise testing. Baseline characteristics of the subjects are shown in table 1. None of the subjects were professional athletes, but mostly well trained (6.5 ± 3.1 hours sport/week). During the study period one participant dropped out because of an injury not obtained during the exercise testing. The study was carried out in conformity with the ethical standards laid down in the 1975 declaration of Helsinki and has been approved by the Institutional Review Board of the Department of Sport Science, University of Innsbruck.

The participants performed three incremental exercise tests to exhaustion at the same time of day, separated by 7 days within a 3-week period. To avoid learning effects the order of the different exercise tests was randomized. Test protocols were designed to yield similar test durations ranging between 7-17 minutes [22,23]. For the treadmill (quasar med, h/p/cosmos) test a 3-min warm up period at a speed of 4 km/h and a slope of 12% followed by an adapted Bruce ramp protocol with 1 minute stages (American College of Sports Medicine 2006) was adopted. To perform the cycle ergometer test an electronically braked cycle ergometer (ergoline, ergoselect) was used. The saddle and handle bar positions of the ergometer were adjusted to resemble the subject's own bike setup. Pedal rate had to be held over 70 rpm throughout testing. The test started after a warm up performed at 50 W for 3 min. Afterwards the workload (P) was increased by 25 W every minute until subjective exhaustion of the participant or the pedal

rate dropped below 70 rpm. The stepper ergometer test was performed on the CS (Diagnostic pedal, Ergospect) with the same protocol that was used by the cycle ergometer test. All subjects were asked to hold a given rhythm throughout testing, which complied with 70 rpm pedal rate on the cycle ergometer. When the participants could not hold the rhythm anymore, the test was terminated. During all tests subjects were verbally encouraged to continue until exhaustion.

Physiological measurements

During the exercise tests, oxygen uptake (VO_2), carbon dioxide output (VCO_2) and minute ventilation (VE) were recorded continuously using a gas analysing system (Jaeger Oxycon pro, Carefusio). Heart rate (HR) was monitored by a Polar heart rate sensor (Polar heart rate sensor H2, Polar). Blood lactate concentration (La) was determined by spectrophotometry (C_line, EKF-Diagnostik Biosen). Arterialized blood samples were taken from an ear lobe prior to each testing session and directly after the end of each exercise. A subjective rating of perceived exertion (RPE), subdivided into systemic and muscular exertion, was obtained using the Borg scale [24-26]. The criteria used to confirm that VO_2 had reached maximum values were: maximal respiratory exchange ratio (RER_{max})>1.1, La_{max}>8.0 mmol/l, HR_{max}>220 bpm minus age and a levelling off of VO_2 despite increasing workload [5,27]. 30 sec means of VO_2, VE and RER were taken as maximal values (HR_{max}, VO_{2max}, VE_{max}, RER_{max}). According to [28] P_{max} was charged in aliquot parts for each second for the cycle ergometer and cardio stepper.

CS description

The CS has been especially designed to stress test the cardiovascular system in a whole body MRT (Figure 1). It is completely built of synthetic and fiber reinforced plastic materials to avoid interferences of the magnetic field and artefacts of the imaging. Therefore the device can be used in all scanners with a field strength of 1.5-7 Tesla and even higher. The design is similar to a "stairwalker" exercise machine with two feet. The two pedals are linked with a hydraulic system, the load on the pedals can be adjusted with a pneumatic driven, remote controlled hydraulic restrictor. Each pedal is equipped with a force sensor. The physical parameters power, work and frequency are calculated in combination with a pedal position sensor. In the "ergometer mode" the module is able to control the adjusted workload automatically (frequency-independent). The technical data are: Pedal displacement: 160 mm, Workload range: 25-450 watt, Frequency: 40-120 Steps per minute

Statistical analysis

Normal distribution of all data was checked with Kolmogorov-Smirnov-tests. A one-way analysis of variance (ANOVA) with repeated measures (cycle, treadmill, CS) and Friedman-tests were used to evaluate significant differences between dependent variables. Significant results were followed by post-hoc comparison using pairwise t-tests and Wilcoxon-tests for intra-group comparison (cycle versus stepper and treadmill versus stepper) and t-tests for independent variables and Mann-Whitney-U-tests for inter-group comparison (men versus women). Data are presented as mean and standard deviation (SD) and a probability level of $p<0.05$ was considered significant.

Results

The cardiorespiratory and metabolic responses during each trial (cycling vs. running vs. stepping) are shown in Table 2. HR_{max}, as well as HR at an RER of 1 (HR_{RER1}) achieved on the cycle ($p<0.001$; $p<0.001$) or the treadmill ($p<0.001$; $p<0.001$) were lower on the CS.

Table 1. Anthropometric data

	male	female	all
	n=24	n=22	n=46
age [a]	31.8 ± 8.3	30.91 ± 9.7	31.4 ± 8.9
body weight [kg]	76.3 ± 7.3	63.7 ± 6.8	70.3 ± 9.4
body height [cm]	178.5 ± 6.8	170.8 ± 5.5	174.8 ± 7.2
BMI	23.9 ± 1.6	21.8 ± 1.7	22.9 ± 2.0
sport per week [h]	7.5 ± 3.2	5.5 ± 2.7	6.5 ± 3.1

Figure 1. MR-conditional cardio stepper

Table 2. Maximal physiologic responses during the three different exercise tests

	all (n=46)			ANOVA	
	Cycle Ergometer	Treadmill	Cardio Stepper	F-value	p-value
P_{max} [Watt]	285 ± 65*	-	199 ± 54	214.76	<0.001
$VO_{2max-abs}$ [ml/min]	3531 ± 1023*	3849 ± 1013*	2971 ± 772	-	<0.001
$VO_{2max-rel}$ [ml/min/kg]	49.9 ± 11.2*	54.4 ± 10.6*	42.0 ± 8.3	167.65	<0.001
HR_{max} [bpm]	186 ± 9*	190 ± 11*	170 ± 13	138.31	<0.001
VE_{max} [l/min]	138 ± 37*	142 ± 32*	112 ± 30	93.93	<0.001
RER_{max}	1.21 ± 0.10*	1.19 ± 0.08	1.18 ± 0.08	4.03	0.025
La_{max} [mmol/l]	10.9 ± 2.9*	11.4 ± 3.1*	9.8 ± 2.7	10.96	<0.001
$RPE_{max-muscular}$	17.5 ± 1.8	16.9 ± 2.0*	17.9 ± 1.8	-	<0.001
$RPE_{max-systemic}$	16.7 ± 2.0*	17.0 ± 2.1*	14.9 ± 2.4	-	<0.001
t_{max} [sec]	745 ± 157*	710 ± 128*	539 ± 130	110.7	<0.001
$VO_{2RER1-abs}$ [ml/min]	2544 ± 861*	3120 ± 938*	2075 ± 633	75.18	<0.001
HR_{RER1} [bpm]	156 ± 20*	166 ± 16*	141 ± 17	91.91	<0.001

P_{max}: maximum power output; $VO_{2max-abs}$: maximum absolute oxygen uptake; $VO_{2max-rel}$: maximum relative oxygen uptake; HR_{max}: maximum heart rate, VE_{max}: maximum minute ventilation; RER_{max}: maximum respiratory exchange ratio; La_{max}: maximum lactate; $RPE_{max-muscular}$: maximum muscular rating of perceived exertion; $RPE_{max-systemic}$: maximum systemic rating of perceived exertion; t_{max}: time maximum; $VO_{2RER1-abs}$: absolute oxygen uptake at RER=1; HR_{RER1}: heart rate at RER=1; *significantly different from stepper (paired t-test)

The HR_{max} was about 9.4% and 11.8% lower compared to the cycle ergometer or treadmill, respectively (Figure 2). However, the target heart rate (85% of the expected maximal heart rate) could be reached with the CS. The average age of the sample was 31.8 years resulting in an expected maximal heart rate of 188.2 bpm. The HR_{max} of 170 ± 13 bpm achieved with the CS amounts to approximately 90%. 18.8% lower $VO_{2max-rel}$ values were observed on the CS when compared to the cycle ergometer (p<0.001) and 29.5% when compared to treadmill (p<0.001) (Figure 2). Lower exercise durations (t_{max}) were detected between the CS and the cycle ergometer (-37.7%; p<0.001) as well as the treadmill (-24.1%; p<0.001). $RPE_{max-muscular}$ values on CS were higher compared to the cycle (p=0.075) and significantly higher compared to the treadmill (p<0.001). $RPE_{max-system}$ showed the lowest values compared to cycle (p<0.001) and treadmill (p<0.001). P_{max} achieved with the CS (199 ± 54 W) was significantly lower (p<0.001) when compared to the values of the bicycle test (285 ± 65 watts).

Table 3 illustrates sex-related differences. There were found no sex-related differences on none of the three devices in HR_{max}. In addition, no sex-related differences for RER_{max} achieved on the CS were found (p=0.216). By contrast, La_{max} and t_{max} differed significantly regarding sex (p=0.025; p<0.001). Females achieved 16.8% lower La_{max} values and 28.5% lower t_{max} values than males.

Discussion

The main outcome of the present investigation is that the target heart rate for a stress CMR can be achieved with the recently developed CS [3-5]. However, as expected the HR values using the CS were 10.5% and 8.6% lower when compared to the cycle ergometer and the treadmill, respectively. The wide workload range (25-450 watt) of the CS enables a stress CMR for nearly all participants, including young and well-trained persons to increase the heart rate to the required extent. By comparison, in other studies stress CMR was performed at heart rates between 110 and 120 bpm [1,29,30], which does not correspond to the required target heart rate of young people.

In the present study nearly all maximal values, except $RPE_{max-muscular}$ during the cycling test and RER_{max} during the treadmill test, were lower on the CS when compared to the cycling and treadmill exercise, respectively. The main reasons responsible for the lower maximal values might be the supine position and the resulting less overall muscle mass involvement and the more pronounced local muscle fatigue on the CS [13,19,20,31]. This is supported by the high muscle
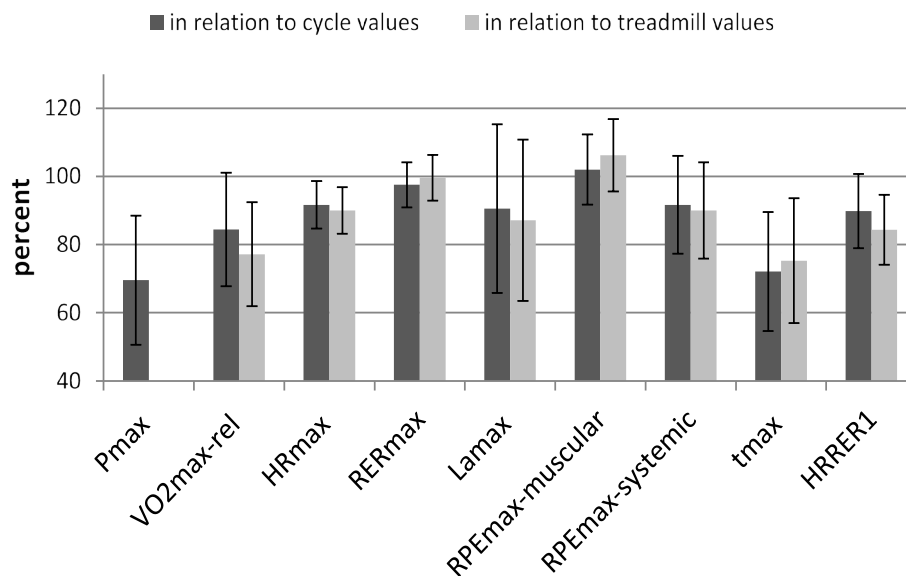
Figure 2. Maximal values of the CS in relation to those of the cycle ergometer and treadmill.

P_{max}, maximum power output; $VO_{2max-rel}$, maximum relative oxygen uptake; HR_{max}, maximum heart rate; RER_{max}, maximum respiratory exchange ratio; La_{max}, maximum lactate; $RPE_{max-muscular}$, maximum muscular rating of perceived exertion; $RPE_{max-systemic}$, maximum systemic rating of perceived exertion; t_{max}, time maximum; HR_{RER1}, heart rate at RER=1; * significant difference from stepper (paired t-test).

Table 3. Gender-related maximal physiologic responses during the 3 different exercise tests

	male (n=24)			female (n=22)		
	Cycle	Treadmill	Cardio Stepper	Cycle Ergometer	Treadmill	Cardio Stepper
P_{max} [Watt]	330 ± 51*	-	235 ± 41	237 ± 39*⁺	-	161 ± 37⁺
$VO_{2max-abs}$ [ml/min]	4265 ± 799*	4605 ± 764*	3556 ± 498	2732 ± 511*⁺	3024 ± 438*⁺	2334 ± 434⁺
$VO_{2max-rel}$ [ml/min/kg]	56.1 ± 10.5*	60.6 ± 10.0*	46.8 ± 6.7	43.1 ± 7.4*⁺	47.7 ± 6.3*⁺	36.8 ± 6.4⁺
HR_{max} [bpm]	185 ± 8*	190 ± 11*	170 ± 13	187 ± 10*	189 ± 11*	171 ± 13
VE_{max} [l/min]	165 ± 24*	166 ± 17*	136 ± 18	108 ± 23*⁺	114 ± 19*⁺	86 ± 15⁺
RER_{max}	1.20 ± 0.12	1.18 ± 0.09	1.17 ± 0.08	1.23 ± 0.09	1.20 ± 0.06	1.20 ± 0.09
La_{max} [mmol/l]	12.1 ± 2.6*	12.7 ± 2.9*	10.7 ± 2.5	9.6 ± 2.7⁺	9.9 ± 2.6*⁺	8.9 ± 2.7⁺
$RPE_{max-muscular}$	17.5 ± 2.1*	17.4 ± 2.1*	18.4 ± 1.5	17.6 ± 1.5	16.3 ± 1.8*	17.4 ± 1.9
$RPE_{max-systemic}$	17.0 ± 1.8*	17.0 ± 1.9*	15.2 ± 1.7	16.4 ± 2.3	17.0 ± 2.4	15.4 ± 3.1
t_{max} [sec]	852 ± 123*	790 ± 107*	624 ± 99	628 ± 94*⁺	624 ± 85*⁺	446 ± 89⁺
$VO_{2RER1-abs}$ [ml/min]	2971 ± 922*	3676 ± 889*	2397 ± 652	2078 ± 473⁺	2513 ± 531*⁺	1724 ± 383⁺
HR_{RER1} [bpm]	152 ± 22*	163 ± 18*	136 ± 19	161 ± 16*	170 ± 13*	145 ± 13

P_{max}: maximum power output; $VO_{2max-abs}$: maximum absolute oxygen uptake; $VO_{2max-rel}$: maximum relative oxygen uptake; HR_{max}: maximum heart rate, VE_{max}: maximum minute ventilation; RER_{max}: maximum respiratory exchange ratio; La_{max}: maximum lactate; $RPE_{max-muscular}$: maximum muscular rating of perceived exertion; RPE_{max}-systemic: maximum systemic rating of perceived exertion; t_{max}: time maximum; $VO_{2RER1-abs}$: absolute oxygen uptake at RER=1; HR_{RER1}: heart rate at RER=1; *significantly different from stepper (paired t-test); ⁺significantly different from males (unpaired t-test)

metabolism values (lactate and RER) reached on the CS, which fulfilled the criteria for the attainment of maximal exertion. These high lactate and RER values could additionally be based on an isometric workload. Due to the restricted movement amplitude on the CS the contraction becomes rather comparable to an isometric muscle contraction, and tends to result in a faster muscle fatigue [32]. This is directly expressed in lower time values (CS t_{max}: 539 ± 130 sec), which could be responsible for the lower maximal values (i.e. VO_{2max}) reached on the CS. The faster muscle fatigue on the CS is also supported by the high $RPE_{max-muscular}$ and the lower $RPE_{max-system}$ values.

There were no sex-related differences in HR_{max} during the exercise on the CS which allows to conclude that cardiopulmonary exercise testing on the CS results in similar responses between men and women.

Some limitations have to be mentioned. For the CS a workload increase of 25 W every minute may be too high, mainly for women as the exercise test duration (446 ± 89 sec) was of borderline [22,23].

Consequently, a lower increase of the workload is recommended for further studies. Furthermore, the fitness level of our young, healthy and well-trained participants was clearly higher compared to the general population and even more when compared to patients. Typically, patients with an indication for a stress CMR are older and less fit. The transfer of our data to the patients might therefore be limited. However, due to the very low minimum workload of 25 W and the minimum load increases of 1 W the device should also be applicable to this population. Additionally, it has to be mentioned that, especially older patients, will need some time to get used to this new technique.

Conclusion

In conclusion, although the maximal cardiorespiratory responses on the CS are somewhat lower compared to maximal treadmill or cycle exercise, the target heart rate for a stress CMR of 85% of the theoretical maximal heart rate can be achieved with the MR-conditional CS even in young and healthy subjects.

Competing interests

Authors SB, FM, HG and MB have no conflicts of interest or financial ties to disclose. KM worked as research assistant in the project in which the CS was developed and tested.

Authors contributions

SB, FM, HG, MB, KM: Conceived and designed the experiments. SB, FM: Performed the experiments. SB, FM, HG: Analyzed the data. SB, FM, HG, MB, KM: Wrote the paper.

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