Dynamic Handgrip Exercise: Feasibility and Physiologic Stress Response of a Needle-Free CMR Stress Test

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Abstract

**Purpose:** CMR pharmacological stress-testing is well-established to detect myocardial ischemia. Despite stressor and contrast agents appear rather save, contraindications and side effects have to be considered. Substantial costs are further limiting its applicability. Dynamic handgrip exercise(DHE) may have the potential to address these shortcomings as a physiological stressor. We therefore evaluated the feasibility and physiologic stress response of DHE in relation to pharmacological dobutamine-stimulation by cardiac magnetic resonance(CMR).

**Methods:** Two subgroups were prospectively enrolled: (i)volunteers without relevant disease and (ii)patients with known CAD referred for stress-testing. A both-handed, metronome-guided DHE was performed over 2 minutes continuously with 80 contractions/minute by all participants, whereas dobutamine stress-testing was only performed in group(ii). Short axis strain by fast-Strain-ENCoded imaging was acquired at rest, immediately after DHE and during dobutamine infusion.

**Results:** Eighty middle-aged individuals(age 56±17years, 48males) were enrolled. DHE triggered significant positive chronotropic(HR<sub>rest</sub>:68±10bpm, HR<sub>DHE</sub>:91±13bpm, p<0.001) and inotropic stress response(GLS<sub>rest</sub>:-19.4±1.9%, GLS<sub>DHE</sub>:-20.6±2.1%, p<0.001). Exercise-induced increase of longitudinal strain was present in healthy volunteers and CAD patients to the same extent, but in general pronounced from basal to apical layers(p<0.01). DHE was aborted by a minor portion(7%) due to peripheral fatigue. The inotropic effect of DHE appears to be non-inferior to intermediate dobutamine-stimulation(GLS<sub>DHE</sub>:-19.5±2.3%, GLS<sub>Dob</sub>:-19.1±3.1%, p=n.s.), whereas its chronotropic effect was superior (HR<sub>DHE</sub>=89±14bpm, HR<sub>Dob</sub>=78±15bpm, p<0.001).

**Conclusions:** DHE causes positive ino- and chronotropic effects superior to intermediate dobutamine-stimulation, suggesting a relevant increase of myocardial oxygen demand. DHE appears safe and timesaving with broad applicability. The data encourages further studies to determine its potential to detect obstructive CAD.

Introduction

Cardiac magnetic resonance (CMR) stress testing to quantify myocardial ischemia provides an excellent prognostic value that is noninferior to invasive fractional flow reserve (FFR) measurements and is therefore suggested by current guidelines to direct revascularisation therapy in chronic coronary syndrome [1-5]. Current CMR protocols, however, have certain shortcomings restricting their applicability in a relevant number of patients [6-9]. On one hand, there are safety aspects due to the dependency on pharmacological agents. Myocardial perfusion imaging relies on vasodilating stressors (e.g., adenosine or regadenosone) and gadolinium-based contrast agents. Less commonly used are adrenergic stressors (e.g., Dobutamine) that increase the myocardial oxygen demand and allow to detect coronary insufficiencies by inducible wall motion abnormalities. Although, side effects of these agents are rare, contraindications and complicating risk factors such as hemodialysis, bronchial asthma or ventricular
Arrhythmogenicity have to be critically assessed. Furthermore, long-term implications of gadolinium depositions in the brain remain unclear. On the other hand, the time consuming CMR stress tests cause tremendous running costs for CMR scanners, personnel, and pharmacological agents paired with incomplete reimbursement. These arguments taken together, have led to a hesitant adoption of CMR stress testing in the majority of health care providers worldwide despite its proven benefits. Various physiological exercises were sought to replace these downsides of pharmacological stressors, but neither MR-conditional ergometers, steppers nor treadmills could be established since these protocols were found to be time-consuming and exercise-related body motion severely affected image quality [10].

We aimed to address these shortcomings by dynamic handgrip exercise (DHE) as a modified needle-free physiological stress test. Unlike previously assessed static handgrip maneuvers, we expected a “dobutamine“-equivalent, positive ino- and chronotropic effect in response to repetitive isotonic both-handed contractions without relevant body motion [11-14]. The goal of this study was to assess the feasibility and hemodynamic effect of DHE in healthy volunteers and in relation to varying doses of continuous dobutamine infusion.

**Methods**

**Study population and design**

Participants were prospectively enrolled at our Department between December 2019 and March 2020 after individual signed consent in two subgroups of (i) volunteers without relevant history of disease and (ii) patients with known CAD that were referred for CMR stress testing and underwent dobutamine stress (predominantly due to contraindications to adenosine, e.g. bronchial asthma). All participants answered a specific questionnaire for symptoms (pre- and post-stress), risk factors and relevant preexisting illnesses. Group (i) of healthy volunteers excluded individuals with history, signs or symptoms of a cardiac disease – except mild arterial hypertension or other existing, isolated cardiovascular risk factors. Participants unable to perform DHE, with impaired LV ejection fraction (EF) < 50% patients, evidence of stress-induced perfusion deficit or previous myocardial infarction were excluded. The study was approved by the institution’s ethics committee and was in accordance to the Declaration of Helsinki.

**CMR acquisition protocol**

CMR was performed on a 1.5 Tesla or 3 Tesla clinical scanner (Ingenia and Ingenia CX®, Philips Healthcare, Best, The Netherlands) with a dedicated 32-element cardiac phased array receiver coil. R-wave triggered SSFP cine sequences were acquired in long- (2-, 3-, 4-chamber views) and short axis (apical, midventricular and basal) views with 35 phases per cardiac cycle. As previously described, fSENC was performed as a single heartbeat acquisition [15]. fSENC sequences were acquired at rest and after two minutes of DHE at apical, midventricular and basal short axis layers. The specific study protocols for healthy individuals (group i) performing DHE alone was extended in CAD patients (group ii) with a
dobutamine stress test as demonstrated in Figure 1a. In dobutamine stress, infusion rate started at 10 µg/kg body weight/minute with increments of 10 µg/kg body weight/minute every 3 minutes and a maximum dose of 40 µg/kg body weight/minute. Additionally, fractions of 0.25 mg atropine were substituted to achieve the target heart rate (85% x (220-age)). Three short axis and three long axis cine sequences were acquired at each stress level [16].

**Dynamic handgrip exercise**

DHE was performed with both-sided, metronome-guided rhythmic hand contractions for two minutes (Figure 1b). Commercially available, CMR-capable rubber handgrip rings in three different strengths (30lb, 50lb, 70lb) were offered to the subjects before the scan started. Maximal voluntary contraction (MVC) for each person was quantified by a dynamic handgrip trainer. The handgrip ring, closest to 50% of maximal voluntary contraction (MVC), was chosen for DHE which was performed at a frequency of 80/min, acoustically indicated by a metronome beat over CMR voice communication. In case of premature physical exhaustion, subjects were asked to indicate that by pressing the alert bell and fast Strain-ENcoded magnetic resonance imaging (fSENC) acquisition was immediately initiated. An adequate execution of DHE was supervised by the attending technician via visual control and an adequate heart rate (HR) response, which was controlled continuously by electrocardiogram (ECG) monitoring. DHE was stated as insufficient when hand movement rate continuously dropped below 80/min. Shortly before finishing the two minutes of handgrip exercise, the subjects were advised to hold their breath after expiration to start fSENC sequence manually.

**Image analysis**

Analysis of ventricular volumes, LV myocardial mass and LV ejection fraction (LVEF) were derived from short- and long axis slices on commercially available workstations (IntelliSpace Portal®, Philips Healthcare) and a dedicated post-processing software (cvi™ v5.5, Circle Cardiovascular Imaging, Calgary, Canada) from CMR-experienced physicians. Dobutamine stress was analysed according to current CMR interpretation guidelines [17].

For the interpretation of fSENC sequences and measurements of longitudinal strain at rest, after DHE and during dobutamine stress, a dedicated software (MyoStrain 5.2.1 Myocardial Solutions, Inc., Morrisville, North Carolina, USA) was used (Figure 2): endo- and epicardial borders were drawn manually at end-systole for each short-axis slice resulting in segmental and global longitudinal strain values. The examiners underwent specific training for the MyoStrain® software. For intra- and interobserver variability, 10 randomly selected subjects were analyzed twice. As reported before [18,19], GLS response after DHE was classified as stable (ΔGLS ≥ -0.5% and ≤ 0.5%), increase (ΔGLS < -0.5%) and decrease (ΔGLS > 0.5%).
Statistical methods

A dedicated software, MedCalc™ v17.7.2 (MedCalc software, Mariakerke, Belgium) was used for statistical analysis. Normal distribution was assessed using Shapiro-Wilk test. Continuous parameters were expressed as mean ± standard deviation for parametric and as median with interquartile range (IQR) for nonparametric variables. For the comparison of continuous variables between two groups, Student’s t-test and Mann Whitney U test were used as applicable. Not normal distributed continuous variables were tested for differences using the nonparametric Wilcoxon test. The intra- and interobserver variability was described using the intra-class correlation coefficient (ICC with 95% CI) with a two-way random model with absolute agreement. A p-value of < 0.05 was regarded as statistically significant.

Results

Study population. Eighty middle-aged individuals including two subgroups of healthy individuals (i) and CAD patients (ii) (mean age 56 ± 17 years; 48 males) were enrolled (Table 1). All subjects were in sinus rhythm. CMR revealed regular biventricular function and morphological dimensions in all individuals (LVEF 62 ± 6%, LVEDV 145 ± 33ml, LV mass 103 ± 28g). Fifty-two subjects (65%) underwent the study examination on 1.5 Tesla MR scanner, the others on a 3 Tesla clinical MR scanner. Mean systolic blood pressure at rest was 124 ± 10mmHg, diastolic blood pressure at rest was 78 ± 7mmHg.

Dynamic handgrip exercise. Seventy-four persons (93%) fully completed DHE, a minor portion of six persons (7%) had to abort prematurely due to peripheral fatigue (Table 1). The lightest handgrip ring resistance (30lb) was used by the majority of subjects (74%), whereas 25% relied on medium resistance (50 lb) and a single person utilized the highest resistance (70lb).

Mean resting HR was 68 ± 10 bpm. DHE induced a significant increase of HR to 91 ± 13 bpm (p < 0.001, Figure 4A). Figure 3 shows a representative course of HR during DHE in a healthy subject. HR increased steadily as DHE progressed. A HR plateau was not evident after two minutes of DHE. After the end of DHE, HR fell rapidly towards the resting HR.

GLS_{rest} was -19.4 ± 1.9%. GLS significantly increased to -20.6 ± 2.1% (p < 0.001) following DHE, according to a relative increase of 7 ± 7%. The majority of our study population (70%) responded with a relevant increase of GLS (DGLS < -0.5%) on a paired comparison, whereas GLS remained unchanged in 25% of individuals and decreased in 5% (Figure 4B). On a segmental level (Figure 4C), DHE induced a significant increase of LS in every segment of apical and midventricular layer (p < 0.01). However, in most basal segments no significant changes of LS could be observed.

Subgroup analysis of CAD patients. Patients in subgroup ii (CAD patients) had a mean age of 64±15 years (23 men, 77%). 4 patients (13%) aborted DHE due to peripheral fatigue. Compared to subgroup i, no significant differences were observed for HR at rest and after DHE (p = n.s.). In subgroup ii, GLS also increased significantly after DHE (GLS_{rest}: -18.8 ± 2.2% vs. GLS_{rest}: -19.5 ± 2.3%, p < 0.001).
In comparison to intermediate dobutamine stress (Figure 5), a significantly higher HR (HR_{DHE}: 89 ± 14bpm, HR_{DobuInterm}: 78 ± 15bpm, p < 0.001) as well as a trend towards a higher GLS was observed after DHE in subgroup ii of CAD patients (GLS_{DHE}: -19.5 ± 3.1%, GLS_{DobuInterm}: -19.1 ± 3.1%, p = 0.22). At peak dobutamine/atropine stress, heart rate was significantly higher compared to DHE and rest (HR_{DobuMax} = 140 ± 12bpm, p < 0.001), GLS though was significantly lower (GLS_{DobuMax} = -15.6 ± 3.6%, p < 0.001).

However, fSENC sequences were not evaluable in 14 patients at maximum stress level (47%). Whilst physiologic DHE stress including the acquisition of fSENC sequences at rest and after DHE took at median 2:20 (2:01-3:23) min, intermediate dobutamine stress already lasted 6:20 (6:02-6:58) min and maximum dobutamine/atropine stress 19:36 (18:03-22:04) min – implying a significant time saving of DHE-fSENC (p < 0.001).

Subgroup analysis of subgroup i (healthy individuals) for gender and age differences. Gender-related subgroup analysis revealed no significant differences regarding LVEF (p = n.s.). Significantly more women used the lowest (30lb) handgrip ring (24 women (96.0%) vs. 12 men (48.0%), p < 0.001). No significant gender differences were found for HR_{rest} and HR_{DHE}. In contrast, GLS_{rest} (men: -19.0 ± 1.3%, women: -20.5 ± 1.5%, p < 0.001) and GLS_{DHE} (men: -20.5 ± 1.5%, women: -21.9 ± 1.3%, p < 0.05), but not DGLS (men: -1.7 ± 1.1%, women: -1.3 ± 1.4%, p = n.s.) were significantly different between male and female subjects.

Divided at the median age (53.7 years), two age-dependent subgroups were created: younger (n=25, mean age = 36.8 ± 10.4 years) and older adults (n=25, mean age = 65 ± 7 years). Except HR_{DHE} (young HR_{DHE} = 96 ± 12bpm vs. old HR_{DHE} = 88 ± 12bpm; p < 0.05), no significant differences were observed between younger and older adults related to DHE study. Neither age, gender nor handgrip ring strength were significant confounders for heart rate or GLS stress response.

Observer variability. Quantification of both GLS_{rest} and GLS_{DHE} by fSENC featured an excellent reproducibility. ICC for the intraobserver variability of GLS_{rest} was 0.98 (95% CI: 0.93-1.00), for the interobserver variability 0.98 (95% CI: 0.95-1.00). For GLS_{DHE}, the ICC for intraobserver variability was 0.99 (95% CI: 0.89-1.00) and for interobserver variability 0.97 (95% CI: 0.88-0.99).

Discussion

In our study, we examined the feasibility of DHE and its hemodynamic effects. We found a positive chrono- and inotropic response to DHE expressed by a significant increase of GLS and heart rate after DHE. The effect strength of DHE is non-inferior to intermediate dobutamine-stimulation. Furthermore, the reasonable low DHE abortion rate supports the practicability of the approach.

As a potential alternative to conventional stress testing, exercise-CMR allows for a needle-free protocol without pharmacological side effects. Due to its simple and favorable handling, DHE represents a cost- and timesaving physiologic stressor. Although, the hemodynamic impact of DHE doesn't achieve standard target heart rate criteria (≥85% of maximum heart rate), strain imaging had demonstrated in the
past to allow the detection of ischemia at intermediate dobutamine-stimulation with high accuracy using Strain-ENCoded CMR [20]. As shown in our subgroup of CAD patients, DHE achieved a comparable or slightly higher increase of HR and longitudinal strain than intermediate dobutamine stress. Due to its similar chronotropic and inotropic effects, DHE represents a promising, needle-free stressor to induce ischemia. Future, prospective trials in CAD patients should determine the potential of DHE-fSENC for the detection of obstructive CAD.

In order to detect segmental stress-induced functional impairment, fSENC appears to fulfill the prerequisites of a fast and reliable strain assessment unlike other techniques as feature tracking known to struggle with segmental reproducibility or myocardial tagging that appears time consuming in both preparation and acquisition [15,18]. As shown recently by our group, measurements of segmental longitudinal strain using fSENC allowed for the detection of ischemia related wall motion abnormalities after hyperventilation/breath-hold maneuver and during adenosine stress [21].

Remarkably, our data suggest a higher chronotropic effect using repetitive, two-handed exercise compared to other studies using different variations of handgrip exercise [19]. In contrast, previous studies had evaluated isometric one-handed handgrip exercise protocols with a broad range of exercise duration, handgrip application and devices hampering a general comparability [19,22-24]. However, several comparative studies investigated the differences between dynamic and isometric (static) handgrip exercise [25-28]. Although most authors found no significant differences in hemodynamic response, Stebbins et al. observed a significantly higher increase of heart rate, blood pressure and cardiac output with increasing handgrip strengths compared to isometric handgrip protocols. We found in comparison to intermediate dobutamine stimulation, DHE to achieve even higher heart rates reflecting a good chronotropic response. Beyond an isolated increase of afterload as observed in isometric handgrip exercise, in DHE this may be attributed more to an increased production and accumulation of muscle metabolites leading to a higher exercise pressor reflex and greater activation of muscle mechanoreceptors [28].

Regarding the GLS response after handgrip exercise, several authors made different observations [19,23,29,30]. Most recently, Blum et al. examined the response of GLS after an isometric handgrip exercise using fSENC-CMR, as we did [19]. They assumed a limited diagnostic purpose for strain imaging after isometric handgrip exercise due to a heterogenous response of GLS. To our knowledge, data on the GLS response after DHE do not exist so far. In our study population, GLS significantly increased after DHE. The vast majority of 56 subjects (70.0%) had a relevant increase of < -0.5%. Even on a segmental level, LS increased significantly in most segments, which is important for its potential future use in detecting regional impairment in ischemic myocardium. In comparison to isometric handgrip exercise, our results are more homogenous and LS increased significantly in the vast majority of patients suggesting that DHE could be a more suitable protocol for future use with fSENC-CMR.

**Limitations.** In the present study we did not investigate varying durations of DHE and their hemodynamic impact. A prolongation of the stress appears of a potential benefit if tolerated by the patient, as heart
rates did not reach a plateau level. Moreover, continuous heart rate and blood pressure monitoring was not available during stress testing. The non-invasive blood pressure monitoring with a common upper arm cuff did not allow for reliable measurements during the repetitive contractions. Peak exercise blood pressure would have allowed to better understand the development of left ventricular afterload.

**Conclusions**

DHE causes a positive inotropic and chronotropic effect comparable or slightly higher than intermediate dobutamine stress, suggesting a relevant increase of myocardial oxygen demand. In this rather small cohort, DHE appears safe with broad applicability. Even minor differences of LS can be detected fast and reliable using CMR-fSENC. Further studies which investigate the differences of isometric and dynamic handgrip exercise, as well as the influence of one- and two-handed approaches in regard to the response of LS are needed. Nevertheless, the data encourages further studies to determine its potential to detect obstructive CAD as a potential needle-free CMR stress test.

**Abbreviations**

bpm = beats per minute;

CAD = coronary artery disease;

CMR = cardiac magnetic resonance;

DHE = dynamic handgrip exercise;

EF = ejection fraction;

fSENC = fast strain-encoded magnetic resonance imaging;

GLS = global longitudinal strain;

HR = heat rate;

LS = longitudinal strain;

LV = left ventricular;

MVC = maximum voluntary contraction.

**Declarations**

**Funding:** The study received no funding.
Conflicts of interest/Competing interests: Nael Osman is the CSO and founder of Myocardial Solutions, provider of MyoStrain® software for the analysis of fSENC sequences. Christian Stehning is an employee at Philips Healthcare. All other authors declare no conflict of interest, esp. no relationships with industry according to journal policy.

Availability of data and material: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability: -

Authors’ contributions: A Ochs responsible for conception of study design, data acquisition and analysis, statistical assessment, and drafting of the manuscript. M Nippes involved in data acquisition and analysis, statistical assessment and revision of the manuscript. J Salatzki involved in data acquisition and analysis and revision of the manuscript. LD Weberling involved in data acquisition and analysis and revision of the manuscript. J Riffel involved in data acquisition and analysis and revision of the manuscript. M Müller-Hennessen involved in data acquisition and revision of the manuscript. E Giannitsis involved in data acquisition and revision of the manuscript. N Osman involved in data acquisition and analysis and revision of the manuscript. C Stehning involved in data acquisition and analysis and revision of the manuscript. F André involved in data acquisition and analysis and revision of the manuscript. HA Katus involved in conception of study design and revision of the manuscript. N Frey involved in conception of study design and revision of the manuscript. MG Friedrich involved in conception of study design and revision of the manuscript. MM Ochs responsible for conception of study design involved in data acquisition and analysis, statistical assessment, and revision of the manuscript.

Ethics approval: The study was approved by the ethics committee of the University of Heidelberg (medical faculty) and was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments.

Consent to participate: Informed consent was obtained from all individual participants included in the study.

Consent for publication: The authors affirm that human research participants provided informed consent for publication of the images in Figure 2 and 3.

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Tables

Table 1 Baseline characteristics of all individuals (n=80) and divided by subgroups.
|                                   | all individuals (n = 80) | healthy volunteers (n = 50) | CAD patients (n = 30) | p subgroup I vs. subgroup II |
|-----------------------------------|--------------------------|----------------------------|-----------------------|----------------------------|
| **Age [years]**                   | 56 ± 17                  | 51 ± 17                    | 64 ± 15               | < 0.01                     |
| **Male [n]**                      | 48 (60%)                 | 25 (50%)                   | 23 (77%)              | < 0.05                     |
| **Weight [kg]**                   | 77 ± 15                  | 75 ± 13                    | 81 ± 16               | < 0.05                     |
| **Height [cm]**                   | 172 ± 9                  | 172 ± 9                    | 172 ± 9               | n.s.                       |
| **BMI [kg/m²]**                   | 26 ± 4                   | 25 ± 3                     | 27 ± 4                | < 0.05                     |
| **Systolic blood pressure [mmHg]**| 124 ± 10                 | 122 ± 8                    | 128 ± 11              | < 0.05                     |
| **Diastolic blood pressure [mmHg]**| 78 ± 7                   | 76 ± 6                     | 80 ± 8                | n.s.                       |
| **Sinus rhythm [n]**              | 80 (100%)                | 50 (100%)                  | 30 (100%)             | n.s.                       |
| **CV risk factors**               |                          |                            |                       |                            |
| **Hypertension [n]**              | 30 (38%)                 | 7 (14%)                    | 23 (77%)              | < 0.001                    |
| **Hypercholesterinemia [n]**      | 23 (29%)                 | 3 (6%)                     | 20 (67%)              | < 0.001                    |
| **Diabetes mellitus [n]**         | 7 (9%)                   | 0 (0%)                     | 7 (23%)               | < 0.001                    |
| **Family history of CVD [n]**     | 21 (26%)                 | 11 (22%)                   | 10 (33%)              | n.s.                       |
| **Smoker [n]**                    | 15 (19%)                 | 3 (6%)                     | 12 (40%)              | < 0.01                     |
| **Obesity [n]**                   | 23 (29%)                 | 2 (4%)                     | 21 (70%)              | < 0.001                    |
| **Resting CMR parameters**        |                          |                            |                       |                            |
| **Field strength 1.5T [%]**       | 52 (65%)                 | 35 (70%)                   | 17 (57%)              | n.s.                       |
| **LVEF [%]**                      | 62 ± 6                   | 63 ± 5                     | 59 ± 6                | < 0.01                     |
| **LVEDV [ml]**                    | 145 ± 33                 | 142 ± 32                   | 149 ± 34              | n.s.                       |
| **LV mass [g]**                   | 103 ± 28                 | 96 ± 27                    | 114 ± 27              | < 0.01                     |
| **Handgrip exercise**             |                          |                            |                       |                            |
| **DHE completed [%]**             | 74 (93%)                 | 48 (96%)                   | 26 (87%)              | n.s.                       |
| **30lb [%]**                      | 59 (74%)                 | 36 (72%)                   | 23 (77%)              | n.s.                       |
| 50lb [%] | 20 (25%) | 13 (26%) | 7 (23%) | n.s. |
| 70lb [%] | 1 (1%)   | 1 (2%)   | 0 (0%)  | n.s. |

BMI= body mass index; CVD= cardiovascular disease; T= Tesla; LVEF= left ventricular ejection fraction; LVEDV= left ventricular end-diastolic volume; DHE= dynamic handgrip exercise.

**Figures**

**a**

![Survey Cine fSENC DHE fSENC intermediate dobutamine fSENC peak dobutamine fSENC](image)

**b**

![2 min](image) [both-sided](image) 30lb 50lb 70lb [80/min](image) [~ 50% of MVC](image)

**Figure 1**

a. CMR protocol of the DHE study. Additional fSENC-sequences were acquired at rest, after 2 minutes of DHE and (in the subgroup of CAD patients) during intermediate (20 µg/kg body weight/minute) and peak dobutamine/atropine stress (40 µg/kg body weight/minute + atropine). DHE was performed after all standard sequences at rest and before the start of pharmacological stress. b. Illustration of DHE. Both-sided, metronome guided rhythmic hand contractions were performed for two minutes at a frequency of 80/min. Handgrip rubber rings at about 50% of maximal voluntary contraction (MVC) were used. CMR= cardiac magnetic resonance imaging; fSENC= fast strain-encoded magnetic resonance imaging; DHE= dynamic handgrip exercise; CAD= coronary artery disease; MVC= maximal voluntary contraction.
Figure 3

Example of the HR response during DHE of a 29-year-old, male subject. HR increased steadily as DHE progressed. After the end of DHE (120s), HR fell rapidly towards the resting HR within 10 seconds. DHE = dynamic handgrip exercise; HR = heart rate.
Figure 5

a. Heart response in subgroup II after DHE (green) and during dobutamine stress (red). After 2 minutes of DHE, HR significantly increased. HRDHE was significantly higher compared to HR during intermediate dobutamine stress. b. GLS response in subgroup II after DHE (green) and during dobutamine stress (red). GLS significantly increased after DHE. During dobutamine stress, GLS increased at intermediate stress level, before it decreased at maximum dobutamine/atropine stress. Error bars represent the standard error of the mean. HR = heart rate; DHE = dynamic handgrip exercise; GLS = global longitudinal strain.