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RESEARCH

Exercise Stress Electrocardiography Using the Two-Minute Jump Test in Children

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Abstract

Although the treadmill and cycle ergometer are commonly used for exercise stress electrocardiography (ECG) testing, they are often difficult to perform with children. We herein evaluated the utility and safety of the 2-minute jump test (2MJT) as a simple, alternative exercise test. One hundred patients, including 60 male patients, with an average age at study commencement of 10.7±3.5 years (mean±standard deviation) and with no exercise restriction who underwent a cardiac check-up between November 2020 and March 2022 at the study center were included. After recording their resting ECG, they jumped for 2 minutes during ECG recording, and the change in heart rate (HR), ECG findings, and occurrence of adverse events were investigated. As a result, patients jumped 185±60 times in two minutes, and their HR increased from 76±13 beats/min at rest to 172±18 beats/min at peak during the test. Ninety (90%) patients attained the ideal target HR of > 150 beats/minute. During the recovery period after loading, five patients had abnormal ECG findings (ventricular extrasystoles, second-degree atrioventricular block, and atrial extrasystoles in two, two, and one patient, respectively) but completely resolved spontaneously within three minutes. Our findings suggested that the 2MJT is a useful and safe exercise test capable of inducing sufficient increase in HR in a short time in children.

Keywords Two-minute jump test · Exercise stress electrocardiography · Heart rate reserve · Heart rate recovery · Children · Arrhythmia

Abbreviations

AVB	Atrioventricular block
CAA	Coronary artery aneurysm
ECG	Electrocardiography
HR	Heart rate
KD	Kawasaki disease
WPW	Wolff–Parkinson–White
2MJT	Two-minute jump test

Introduction

Exercise stress electrocardiography (ECG) is useful for evaluating exercise-induced arrhythmia and myocardial ischemia under increased oxygen demand and myocardial sympathetic activity. Common indications for this test in children are congenital heart disease, arrhythmia, and Kawasaki disease (KD) with coronary artery aneurysm (CAA) as well as the symptoms of chest pain, palpitations, and syncope [1]. Although appropriate loading is needed to induce a sufficient increase in heart rate (HR) to detect abnormalities on the ECG, there is currently no standardized measure of adequate exercise for this purpose in children. In adults, the target HR is defined as 85% of the maximum HR, which is calculated as 220 - (age) beats/min or 208 - 0.7 x (age) beats/min [2, 3]. Extrapolating this formula to children yields a target HR of 171–178 beats/min for 10-year olds and 168–174 beats/min for 15-year olds. In Japan, routine heart disease screening conducted in schools often detects arrhythmias, such as extrasystoles and atrioventricular block (AVB). The Japanese Circulation Society and the Japanese Society of Pediatric Cardiology and Cardiac Surgery recommend increasing

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the peak HR value to at least 150 beats/min when evaluating cardiac function [1]. The standard exercise test uses a treadmill or a cycle ergometer, both of which are expensive, space-occupying, and originally designed for adult use, making them less than ideal for use with young children. On the other hand, the Master two-step test merely requires two, 23-cm (nine inch) steps and can be easily performed with younger children. However, performing an ECG during this test is relatively difficult, and the HR increments are often insufficient for evaluating exercise-induced ECG even when using the Master triple-step test [4].

The jump test is simple, easily performed with younger children, and is utilized in some medical institutions in Japan. This test involves repeatedly jumping in place for the designated duration and has been performed with pediatric patients with repaired tetralogy of Fallot. The test achieved a peak HR equal to that achieved using the treadmill test more quickly [5]. However, there are few studies of this test, which is still not used globally. We therefore conducted the present, prospective study to evaluate the utility and safety of the jump test.

Materials and Methods

Patient Selection

The present, monocentric, prospective, observational study enrolled patients who had visited the outpatient cardiology clinic at Tokyo Metropolitan Children's Medical Center between November 2020 and March 2022, met all the selection criteria, and did not meet any of the exclusion criteria. The inclusion criteria were (1) age < 20 years; (2) no exercise restrictions; (3) history of an ECG abnormality, such as arrhythmia, congenital heart disease, myocardial disease, coronary artery disease, KD with CAA, or cardiac symptoms, such as palpitations, chest pain, or syncope; and (4) ability to exercise under the direction of a healthcare provider. Patients with (1) congenital heart disease who had not yet undergone intracardiac repair; (2) postoperative univentricular repair; or (3) a high risk of circulatory compromise or any of the contraindications for exercise testing listed by the American Heart Association [6] were excluded.

Testing Procedure

After at least ten minutes of rest, the subjects were fitted with a wristwatch with an automatic HR monitor (Apple Watch Series 5; Apple, Cupertino, California, United States) to measure their HR. After recording the resting 12-lead ECG in the supine position for 1 minute, the subjects were asked to stand while wearing the ECG and jump in place for two minutes while being observed by a pediatric cardiologist. They were encouraged to jump as high and as many times as possible (Fig. 1). The target jump height was 20 cm more than the subject's height for children aged less than 8 years, 30 cm above the subject's height for children aged 9–13 years, and 40 cm above the subject's height for children aged 14 years or older based on previously reported reference values for vertical jump heights in healthy children [7]. If a subject complained of fatigue or had difficulty continuing, the test was terminated for the patient's safety. A cardiologist was present to attend to any complications that might occur during the test.

The peak HR during jump loading and the duration to the peak HR were recorded afterward by referring to the ECG waveform and the values recorded by the wristwatch HR

Fig. 1 Scene from the test. The subject began jumping after a 12-lead ECG was attached (**1a**). The subject was barefoot, and a mat was placed on the floor. Two technicians were present; one measures the time and number of jumps and the other encouraged the patient to jump while holding the ECG electrode lead wires in a bundle to avoid tangling (**1b**).

monitor. The subjects were placed in a supine position on a bed immediately after loading, and their HR was recorded for at least 3 minutes until it returned to a steady state. The examination ended when the subject's condition was determined to be stable.

Data Collection

The following data were obtained from the subjects: (1) age, sex, height, weight, underlying disease (or symptoms), and reason for testing (arrhythmia or ischemia evaluation); (2) resting HR, HR at each minute from loading commencement, ECG findings, peak HR during loading (measured by 12-lead ECG and wristwatch), number of cases a peak HR < 150 beats/min was achieved, the duration to the peak HR, the total number of jumps, number of extrasystoles, and presence or absence of a Q wave or ST-T changes; (3) medication status; and (4) any occurrence of a fall, sprain, contusion, palpitations, chest pain, or loss of consciousness. The subjects were classified into the following age groups: age < 8 years (youngest age group), age 9–13 years (middle age group), and age 14 years or older (oldest age group).

Outcome Measures

The primary outcome was the peak HR during exercise. The secondary outcomes were (1) difference between the rest and peak HR values, i.e., the HR reserve; (2) HR recovery on cessation of exercise; (3) change in the extrasystole rate (number of extrasystoles divided by the total HR) before and after exercise in subjects with extrasystoles; (4) any correlation between the peak HR values from the 12-lead ECG and the wristwatch monitor; and (5) incidence of adverse events.

Statistical Analysis

Descriptive statistical analysis was performed using the mean ± standard deviation for continuous variables, such as age, height, weight, HR, number of jumps, and the duration to the peak HR. A percentage was used to express nominal variables, such as sex, underlying disease, reason for testing, and ECG findings. Analysis of variance was performed to compare the continuous variables, and Tukey's test was used to compare items differing significantly among the groups. The unpaired *t* test was used to compare sex-related differences. Any correlation between the 12-lead ECG and the peak HR recorded by the wristwatch monitor was analyzed using correlation coefficients. All statistical analyses were performed using SPSS Statistics version 28 (IBM, Armonk, New York, United States). Two-tailed $P < 0.05$ was considered to indicate statistical significance.

Results

Table 1 shows the characteristics of the 100 subjects included in the study. Fifty-nine (59%) patients were evaluated for arrhythmia (e.g., extrasystoles), and 41 (41%) were evaluated for myocardial ischemia (e.g., KD with CAA). Twenty-one (21%) patients were receiving a medication for a heart disease, including 16 subjects receiving aspirin or warfarin for antithrombotic therapy after KD. Beta-blockers had been prescribed to three patients with idiopathic ventricular tachycardia, paroxysmal supraventricular tachycardia, or repaired transposition of the great arteries.

Figure 2 shows the changes in HR over time after exercise. Overall, 185±60 jumps were performed for 2 minutes, and the HR increased from 76±13 beats/min at rest to a peak of 172±18 beats/min. Ninety (90%) patients exceeded an HR of 150 beats/min during the jump test. The HR reserve was 96±19 beats/min, and the duration to the peak HR was 110±12 s after commencement of testing.

The jump frequency in the youngest, middle, and oldest age group was 180±72, 204±50, and 167±55, respectively, with the oldest age group having significantly fewer jumps than the middle age group ($p = 0.005$). The resting HR value was significantly higher in the youngest age group than in the middle age group (81 ± 11 vs. 72 ± 11 beats/min, $p < 0.001$), and the HR reserve was lower in the youngest age group than in the middle age group (88 ± 20 vs. 99 ± 16 beats/min, $p = 0.02$). The oldest age group had a significantly higher HR value at all time points during the recovery period than the middle age group ($p < 0.05$). A comparison of the resting and peak HR values by sex and age group revealed that male subjects in the oldest age group tended to have a higher peak HR value than female subjects (182 ± 12 vs. 171 ± 17 beats/min, $p = 0.05$) (Fig. 3). There was no significant, sex-related difference between the other age groups.

HR measurement using the wristwatch monitor was able to be performed in 63 patients (63%). The difference with the peak HR value recorded by 12-lead ECG was -6 ± 11 beats/min, showing good correlation (correlation coefficient 0.85; $p < 0.001$) (Fig. 4). In 20 (20%) patients with extrasystoles, the number of extrasystoles per 30 s decreased significantly from 8.4 ± 9.5 (20 ± 19%) to 2.2 ± 4.0 (3 ± 5%) ($p = 0.002$) and completely resolved in 12 subjects (60% of extrasystoles).

There were no complications associated with the test, such as falls, and all the subjects were able to complete the 2-minute jump test (2MJT). No new cases of arrhythmia were observed during loading, but during the recovery period, ventricular extrasystoles, second-degree AVB, and

Table 1 Patient characteristics by age group

	Total	Youngest age	Middle age	Oldest age
No. of patients	100	32	38	30
Age (years)	10.7 ± 3.5	6.5 ± 1.2	11.1 ± 1.4	14.8 ± 0.8
Male sex	60 (60%)	18 (56%)	28 (74%)	14 (47%)
Height (cm)	142 ± 19	119 ± 11	146 ± 11	159 ± 9
Weight (kg)	37 ± 13	23 ± 5	38 ± 8	50 ± 8
Reason for test: arrhythmia	59 (59%)	24 (75%)	17 (45%)	18 (60%)
Ventricular extrasystoles	21	9	6	6
WPW syndrome	11	5	2	4
Atrial extrasystoles	5	3	1	1
Syncope	4	2	1	1
Second-degree AVB	4	1	1	2
Prolonged QT	3	0	1	2
Palpitation	2	1	1	0
Others	10	4	4	2
Reason for test: myocardial ischemia	41 (41%)	8 (25%)	21 (55%)	12 (40%)
KD with CAA	22	2	15	5
Heart disease	12	4	6	2
Chest pain	8	2	2	4
Others	4	1	1	2

Data are expressed a percent or mean ± standard deviation

Classification into more than one underlying disease or symptom category was possible

AVB atrioventricular block; *CAA* coronary artery aneurysm; *KD* Kawasaki disease; *WPW* Wolff–Parkinson–White

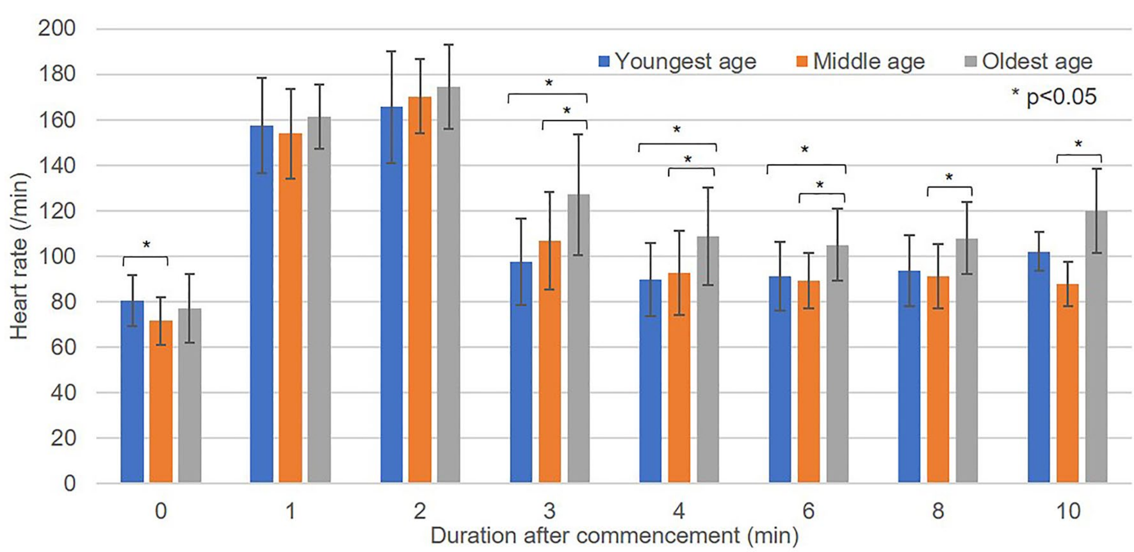

Fig. 2 Post-load HR by age group

atrial extrasystoles were observed in two, two, and one subject, respectively. These findings were not observed at rest, and all of them resolved within the subsequent 3 minutes. None of the patients complained of any symptoms, such as chest pain or palpitations.

Discussion

The present study demonstrated the ability of the 2MJT to reach the target HR in children. None of the subjects

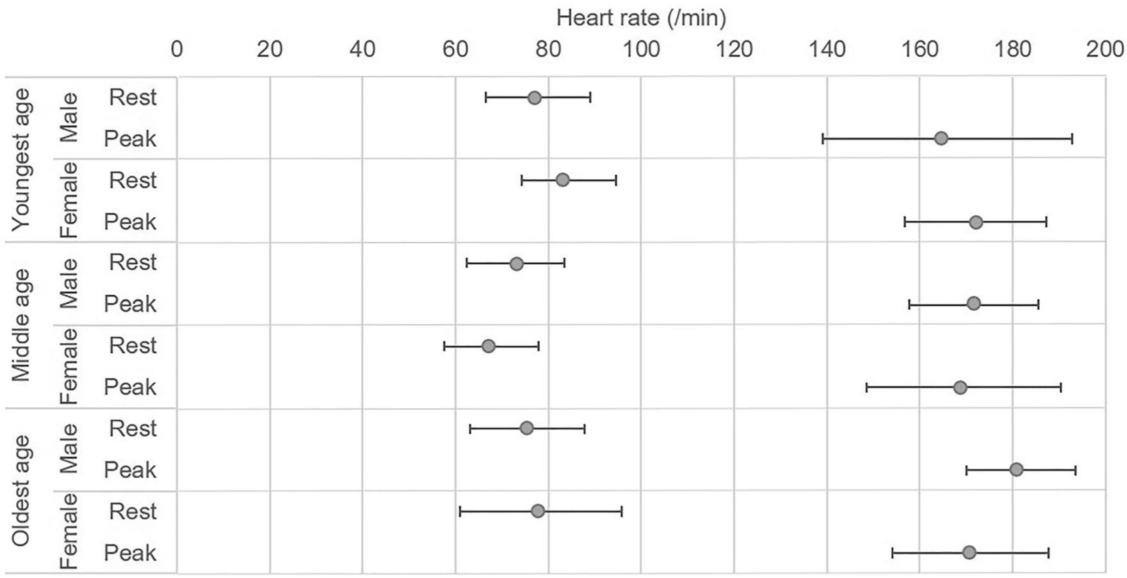

Fig. 3 Resting and peak HR values by sex and age

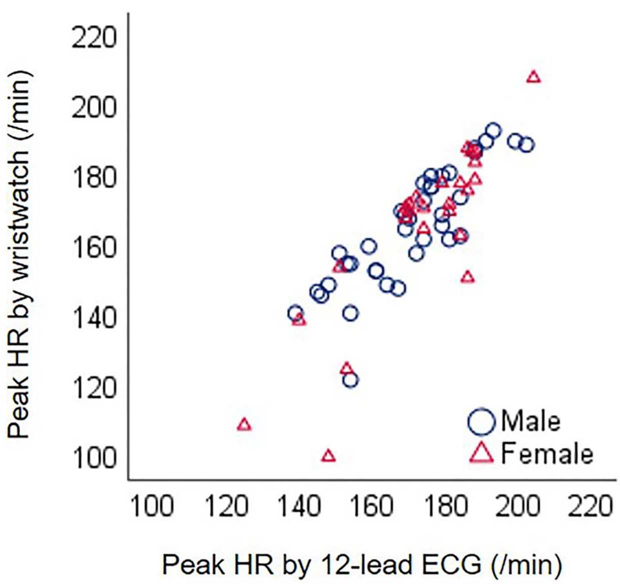

Fig. 4 Comparison between the peak HR values recorded by 12-lead ECG and wristwatch monitor

dropped out during the loading period. When the exercise load was uniformly applied for two minutes, the peak HR value was induced within 110 ± 12 s after the commencement of exercise. Although the HR could have been increased by extending the loading time, past studies reported that the HR reached to a steady state after two minutes of jumping [5]. The 2MJT was able to induce an adequate HR increase for two reasons: (1) the target jump height was shown to the subjects, resulting in keeping the constant quality of the test and (2) the ECG electrodes were worn during exercise loading, thus enabling continuous recording before, during, and after loading as well as recording of the "true" peak HR immediately after loading. A previous study reported that in 63 healthy children who underwent a treadmill stress test [8], the peak HR induced by jump loading corresponded to Stage IV ~ V in the Bruce protocol, suggesting the utility of the 2MJT as a cardiac exercise test. Furthermore, the length of the test was ideal, especially for young children, who may become less cooperative during a lengthy test.

The 2MJT also has the advantage of being a cost-effective screening test because it does not require special equipment or space; it can be performed in hospitals that cannot afford the cost of special equipment (e.g., in developing countries) or have no extra space to accommodate such equipment. On the other hand, it is not indicated for patients with a high risk of arrhythmia exacerbation or ischemic changes caused by exercise, given the short duration and high load involved. In such subjects, a standard treadmill or cycle ergometer test is more appropriate for stepwise exercise load.

The differences in the results by age and gender may be understood in the following way. The high resting HR value in the youngest age group can be explained by the normal decrease in HR accompanying aging. The oldest age group had a high peak HR value despite having a small number of jumps possibly because of the strong load applied in the higher jumps. In addition, the difference in physical strength between male and female subjects in the oldest age group may have contributed to the higher HR value of the male subjects. In the oldest age group, however, the HR returned to the normal range more slowly after testing. HR recovery involves regulation by the autonomic nervous system, which typically shows increased parasympathetic activity within one minute after the end of exercise and decreased sympathetic activity thereafter [9]. Recovery of the HR is known to decrease with age in children, implying impaired activity of the parasympathetic component of the autonomic nervous system [10]. The present results were consistent with this fact.

In terms of adverse events, no subject experienced deterioration of extrasystoles or AVB, ST-T changes, or subjective symptoms during loading, and all the subjects were able to take the test. The ECG findings worsened in five patients after loading. These findings were previously noted in all the subjects and re-emerged during the recovery period when parasympathetic activity predominates. In adults, frequent ventricular extrasystoles during recovery reportedly increased the risk of mortality [11, 12], but their effect on children is unclear.

The present study evaluated HR changes using the new, commercially available wristwatch monitor. Owing to data synchronization problems, measurements were able to be made in only 63% of the subjects, but the data from the monitors correlated well with the ECG data. The latest model (Apple Watch Series 7; Apple) can display an ECG similar to lead I and is reportedly useful for early detection of arrhythmias, such as atrial fibrillation [13]. Apple's official website states that their wristwatch monitor is not a medical device and is not intended for use by children under 22 years of age. Nonetheless, our data suggest that it may be useful as an easy method of measuring HR in children.

The present study has several limitations. First, the patient background was heterogeneous, with some subjects having arrhythmia or a cardiac disease, some receiving oral beta-blockers, many having KD with CAA, and some having no underlying disease at all. These conditions may affect HR response during exercise stress. Second, because expiratory gas analysis cannot be applicable in the present method, exercise tolerance was unable to be assessed using the gas exchange ratio, anaerobic metabolic threshold, or maximal oxygen uptake. Third, in cases in which the target HR was not achieved after loading, new findings associated with elevated HR may have been overlooked. Fourth, the ECG during loading had large artifacts, making it difficult to analyze the QT time and ST segment, which were evaluated with the ECG immediately after loading.

Conclusion

The exercise stress test using the 2MJT is an effective and safe method of testing for arrhythmia and myocardial ischemia even in young children by inducing a sufficient increase in the HR in a short time. This method of testing does not require special equipment or space and has few associated adverse events, whereas the post-loading dynamics were different by age and gender.

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Data Availability Not applicable.

Code Availability Not applicable.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interest to disclose.

Ethical Approval This study was conducted in accordance with the ethical principles of the Declaration of Helsinki (as amended by Fortaleza in 2013) and the Ethical Guidelines for Life Sciences and Medical Research Involving Human Subjects (enacted by the Ministry of Education, Culture, Sports, Science and Technology, Ministry of Health, Labor and Welfare, and Ministry of Economy, Trade and Industry in Japan on March 23, 2021). This study was approved by the Ethics Committee of the Tokyo Metropolitan Children's Medical Center (Approval No. 2020b-60).

Consent to Participate Verbal informed consent was obtained prior to the study and was noted in the electronic medical records.

Consent to Publish The authors affirm that the subjects provided their informed consent for the publication of the images in Figs. 1a and 1b.

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