Responses of Normal Children and Young Adults to Controlled Bicycle Exercise

FREDERICK W. JAMES, M.D., SAMUEL KAPLAN, M.D., CHARLES J. GLUECK, M.D.,
JAI-YEONG TSAY, PH.D., MARY JO S. KNIGHT, E.T., AND CATHERINE JESSIE SARWAR, B.A., E.T.

SUMMARY **Exercise responses were obtained from 149 children and young adults (average age 14.5 years) and divided by sex and body surface area (BSA): children with BSA < 1 m^2; children with BSA 1–1.19 m^2; males with BSA ≥ 1.2 m^2; and females with BSA ≥ 1.2 m^2. Total work, mean and maximal power outputs were more affected by body size (height) than age in children with BSA < 1 m^2 and in males and females with BSA ≥ 1.2 m^2. Mean systolic pressure increased up to 64% above the preexercise supine value at peak effort, with the level of mean maximal systolic pressure having a positive relationship with body size (height), power output and preexercise sitting systolic pressure in all subgroups except children with BSA 1–1.19 m^2. Mean diastolic pressure increased up to 24% above the preexercise supine value at peak effort. ST-segment depression of 1–2 mm was recorded in 12.1% (18 of 149) of the population at peak exercise. These changes occurred in 8.9% of all males and in 16.9% of all females ($p > 0.1$). The data from this study reveal the importance of sex and body size in the clinical interpretation of exercise responses in growing subjects, provide a reference for objective evaluation of subjects with or without cardiac abnormalities and provide a guide for careful monitoring of subjects during an exercise study.**

EXERCISE TESTS are becoming an integral part of the diagnostic evaluation of children and young adults with cardiac disorders.[1-6] Preliminary studies have indicated that selected variables such as cardiovascular and ventilatory responses, working capacity and the ECG contribute greatly to the success of the exercise procedure in revealing significant abnormalities that may influence the clinical management of young patients.[1, 4, 7-12] Several exercise protocols using the bicycle ergometer have been reported.[13-15] However, exercise data for normal children using these protocols are often incomplete and difficult to interpret and apply to young subjects undergoing clinical evaluation.

We have extensively used a fixed, continuous, progressive bicycle exercise protocol and recorded multiple variables while testing. Our experience has shown that this approach is feasible in very young children as well as adults. In this study we report values for total work, rates of work, heart rate, blood pressure and changes in the ECG at peak voluntary effort during upright bicycle exercise in a population of normal children and young adults. The normal data from this study will provide a reference for objective clinical evaluation and longitudinal follow-up of subjects with or without cardiovascular abnormalities and may serve as a guide for careful monitoring during an exercise procedure.

From the Division of Cardiology, Children's Hospital Medical Center, Cincinnati, Ohio.

Supported in part by grant 5RO1 HL18454-02 and grant 1-T32-HL07417-01, NHLBI, grant 76 853 from the American Heart Association, and the American Heart Association, Southwestern Ohio Chapter.

Address for correspondence: Frederick W. James, M.D., Division of Cardiology, Children's Hospital Medical Center, Cincinnati, Ohio 45229.

Received February 12, 1979; revision accepted November 29, 1979.

Circulation 61, No. 5, 1980.

Materials and Methods

Subjects

One hundred forty-nine healthy subjects (90 males and 59 females), ages 5–33 years (average 14.3 years), underwent one or more bicycle exercise procedures in the Clinical Cardiovascular Laboratory. Twelve subjects (7.5%) were between 22–33 years at the time of the exercise test. The study population included volunteers, participants from lipid sampling studies[16] and referrals to the cardiac clinic for evaluation of nonspecific chest pain or cardiac murmurs. Racially, the population was 95% white and 5% black.

All subjects met the following criteria for entrance into the study:

1) Normal physical examination, including normal resting blood pressure as determined by reported values[17-20] for subjects 18 years or younger and a blood pressure < 140/90 mm Hg for subjects over 18 years during the 3-month period before the exercise test.

2) Normal resting ECG, including the absence of documented atrial or ventricular arrhythmia before the exercise test.

3) Normal plasma cholesterol and triglycerides after 12 hours of fasting.

The blood lipid studies were drawn and determined in the Lipid Research Center. The blood lipid levels in 103 of 149 subjects have been reported elsewhere.[16] Thirteen subjects (one girl with body surface area (BSA) < 1 m^2; three girls and one boy, BSA 1–1.19 m^2; and five males and three females, BSA ≥ 1.2 m^2) were actively participating in athletics. The physical activities of the remaining group did not exceed the levels appropriate for common recreational events, school or employment. Consequently, the physical training level of this study population was considered to be a reasonable sampling distribution of subjects within the pediatric and young adult age groups.

Exercise Procedure

Each subject underwent a continuous, progressive bicycle exercise test after obtaining informed consent from the parent, guardian or subject. The procedure was usually conducted in the morning with restricted food intake for at least 2 hours before the study. The bicycle protocol in this study is outlined in table 1. The protocol consists of three exercise programs for three ranges of body surface area. These three exercise programs present an adequate challenge for normal subjects of various sizes with similar physical working capacities.[21, 22] All subjects willingly performed the exercise without the presence of parents, friends or relatives in the laboratory. A physician conducted the test and was the primary source of instruction to the subject for necessary tasks during the exercising portion of the test. We found this approach to be successful in obtaining peak performance while measuring several variables during exercise. The test was performed on a bicycle ergometer (Quinton Instruments, Model 845) with a programmer (Model 644) that enabled automatic progression through the preselected exercise program determined by body surface area. The ergometer was returned routinely to the factory for calibration after 18 months of use. During the interim, stability of the instrument was checked every 3 months by measuring oxygen uptake ($\dot{V}O_2$) in the same subject at three work levels (200, 600 and 1200 kg-m/min). The calibration remained relatively stable in that the variation of the quarterly measured $\dot{V}O_2$ was less than 10% of the estimated $\dot{V}O_2$[22] for each level.

The ECG was recorded from the application of 14 electrodes (Hewlett-Packard) to each subject using a multichannel electrocardiograph (Hewlett-Packard 1513A). This approach permitted the recording of 12 conventional electrocardiographic leads and Frank orthogonal leads (X, Y and Z). A 1-mV signal produced a stylus deflection of 10 mm. Three electrocardiographic leads were displayed on an oscilloscope (Statham) during the test. The oscilloscope was calibrated so that a millivolt signal produced a deflection of 20 mm, facilitating early detection of ST-segment changes. Heart rate (beats/min) was computed by averaging the interval between the PQ or PR points of two complete RR cycles on the ECG recorded at a paper speed of 50 mm/sec.

The blood pressure was measured in the right arm in all subjects with a programmed air compression cuff system (Narco-Biosystem Inc. PE-300) operated by remote control. This blood pressure system consistently read 2 mm Hg higher than the mercury sphygmomanometer between the levels of 20–300 mm Hg. The process of selecting the proper compression cuff size adhered to the guidelines of the task force on blood pressure control in children.[19] The cuff was tightly wrapped around the right arm and completely enclosed with an elastic bandage. The pressure levels at the first, fourth and fifth Korotkoff sounds were recorded, with the first and fourth sounds representing systolic and diastolic pressures, respectively.[23] For each measurement of blood pressure, the subject was instructed to relax the right arm at his or her side while pedaling the ergometer.

Before exercise, a conventional 12-lead ECG and Frank orthogonal leads (X,Y and Z) were recorded in the supine and standing positions with and without hyperventilation. These maneuvers were used to provoke arrhythmia, T-wave or ST-segment changes. The electrocardiographic leads (usually V_1, V_5 and V_6) were observed on the oscilloscope for 20–30 minutes for detection of arrhythmia before testing. Heart rate and blood pressure were recorded in the supine position and while sitting on the bicycle ergometer.

During exercise, each subject maintained a constant pedaling speed of 60–70 rpm on the bicycle during automatic increases in work loads from a preselected exercise program. The electrocardiographic leads were simultaneously recorded every minute. Other electrocardiographic leads were scanned and recorded when arrhythmia or ST depression appeared on the oscilloscope. Heart rate was computed for each minute of exercise and immediately before the end of the test. Blood pressure was measured in the right arm every 1–2 minutes.

The exercise continued to a level of exhaustion, which identified the peak level of voluntary effort. In all subjects, that level of exertion produced a

TABLE 1. *Continuous Progressive Exercise Protocol Subdivided into Exercise Programs I, II and III**

	I (BSA < 1 m²) (kg-m/min)	II (BSA 1–1.19 m²) (kg-m/min)	III (BSA ≥ 1.2 m²) (kg-m/min)
Level 1	200	200	200
Level 2	300	400	500
Level 3	500	600	800
Increments	100	100	200

Pedal speed—60–70 rpm; duration of levels—3 minutes.
Adapted from James et al.[4]
*The exercise programs are used for three ranges of body surface areas (BSA). The exercise time at each level is 3 minutes. When three levels are successfully completed, the work load is increased by 100- or 200-kg-m/min increments until the subject reaches a peak level of voluntary effort.

TABLE 2. *Descriptive Data Stratified by Height in Children with Body Surface Area < 1 m² and 1–1.19 m²*

Height (m)	No. of subjects		Weight (kg)	BSA (m^2)	Age (years)	Total work (kg-m)	Mean power (kg-m/min)
Males and females with BSA < 1 m^2 in exercise program I							
< 1.20	9	Mean	21	0.80	6	1222	242
		SD	2	0.03	1	377	20
		Min	19	0.78	5	500	200
		Max	25	0.87	8	1625	262
≥ 1.20	8	Mean	24	0.93	9	2144	290
		SD	1	0.04	1	810	42
		Min	21	0.86	7	1275	245
		Max	26	0.99	12	3750	368
Males and females with BSA 1–1.19 m^2 in exercise program II							
< 1.40	14	Mean	30	1.07	9	2911	358
		SD	3	0.03	1	1652	67
		Min	26	1.01	6	1300	277
		Max	36	1.13	11	8100	540
≥ 1.40	10	Mean	33	1.15	12	3428	384
		SD	2	0.03	1	1349	59
		Min	30	1.11	10	2100	323
		Max	35	1.19	14	5900	484

Abbreviations: BSA = body surface area; DP = diastolic pressure; ET = exercise time; HR = heart rate; MAX PWR = maximal power output; Min, Max = minimal, maximal values; SP = systolic pressure.

respiratory rate ≥ 40 breaths/min with easily audible respiratory sounds and an increased pulse pressure with leveling of systolic pressure and heart rate during the last 2 minutes of exercise. After exercise, the subjects were immediately placed in the supine position to monitor blood pressure, heart rate, and electrocardiogram for 20 minutes.

Reproducibility of the absolute values for total work, rate of work, blood pressure, heart rate and electrocardiographic changes was tested by conducting a repeat exercise test in 31 subjects within 2 months of their initial study.

Data Analyses

For each subject, the total work (kg-m) performed to an exhaustive level during the continuous exercise test was calculated as the sum of the products of work load (kg-m/min) and exercise time (minutes) at each level reached in exercise program I, II or III. Mean power output (kg-m/min) was the total work performed divided by the total exercise time (minutes). Maximal power output (kg-m/min) was the highest rate of work that was reached and maintained for 1.5 minutes or longer during the continuous progressive exercise test.

Maximal blood pressure and heart rate were recorded at the peak level of voluntary effort. These exercise data were divided into four subgroups: 1) boys and girls with BSA < 1 m^2, program I; 2) boys and girls with BSA 1–1.19 m^2, program II; 3) males with BSA ≥ 1.2 m^2, program III; and 4) females with BSA ≥ 1.2 m^2, program III. The exercise data were stratified within each subgroup by height.

The ECG was analyzed at peak exercise for 1) ST-segment depression ≥ 1 mm for ≥ 60 msec below a baseline that connects the PR or PQ junction of three to five consecutive P-QRS-T complexes in any lead;[16] 2) slope of ST-segment (mV/sec) and J-point depression; and 3) distribution of ST-segment changes among the electrocardiographic leads. The ECG was also reviewed for cardiac arrhythmia and T-wave changes before, during and after exercise.

Statistical Analyses

Group means (± SD) for body size, age, work, rate of work and blood pressure stratified by height were calculated. The relationships of units of work (total work, mean power output and maximal power output) to age and body size (height, weight and body surface area), and blood pressure (supine, sitting and maximal) to age and body size were analyzed.[24] The relationships of maximal systolic pressure to resting (supine and sitting) systolic pressures and maximal power output were also analyzed. The frequencies of segmental ST depression ≥ 1 mm between subgroups of the total population were analyzed using chi-square analysis.[25]

TABLE 2. (*Continued*)

MAX PWR (kg-m/min)	ET (min)	Blood pressures and heart rates								
		Supine			Sitting			Maximal		
		HR (beats/min)	SP (mm Hg)	DP (mm Hg)	HR (beats/min)	SP (mm Hg)	DP (mm Hg)	HR (beats/min)	SP (mm Hg)	DP (mm Hg)
267	5.0	95	95	60	103	94	61	195	119	70
50	1.2	7	8	8	16	8	10	17	10	10
200	2.5	80	82	50	78	80	44	160	104	56
300	6.2	100	104	76	120	108	82	220	132	84
375	7.2	84	103	65	87	102	64	191	130	73
103	1.6	13	12	8	15	8	7	18	15	11
300	5.2	60	92	52	75	90	58	160	120	52
500	10.2	100	130	76	120	118	74	220	156	86
493	7.7	82	103	65	85	105	69	194	145	77
121	2.4	11	7	6	27	8	7	16	17	6
400	4.7	60	94	56	70	96	62	160	128	62
800	15.0	100	120	74	102	124	82	220	184	84
540	8.7	84	107	68	94	111	72	199	148	71
135	2.0	11	5	8	17	6	6	14	16	21
400	6.5	70	98	56	70	102	64	166	126	16
700	12.2	100	110	80	120	124	82	220	170	90

Results

Resting and Exercise Periods

Work, Power Output and Heart Rate

In each subgroup work and power output increased with body size and age. (tables 2, 3 and 4). However, total work, mean and maximal power outputs were more affected by body size than age in the children (BSA < 1 m²) and large males (BSA ≥ 1.2 m²) (table 5). For the females with BSA ≥ 1.2 m², the correlation of the units of work to height was stronger than to weight, body surface area or age. In the boys and girls with BSA 1–1.19 m² the relationships of total work, mean and maximal power outputs to body size and age were negligible (table 5). In this same subgroup, the range for body size was narrow compared with the other subgroups.

The coefficients of variation in the height classes of the total population were 12–57% for total work, 6–28% for maximal power output and 6–20% for mean power output. The means for the units of work in these height classes that accomplished different amounts of work and reached different levels of power output were associated with mean maximal heart rates of 187–199 beats/min. The levels of maximal heart rates in the total population were ≥ 200 beats/min in 63.7%, 180–199 beats/min in 26.2%, 160–179 beats/min in 9.4% and less than 160 beats/min in 0.7%. The mean resting heart rates varied with height, but mean supine heart rate tended to decrease with height.

Blood Pressure

In all subjects systolic pressure increased from rest to peak effort with a widening of pulse pressure. For each of the height classes, mean systolic pressure increased up to 5.3% above the supine value in the sitting position and 25–64% above the supine value at peak exercise (tables 2–4). Mean diastolic pressure increased up to 14% above the supine value in the sitting position and 1.4–24% above the supine value at peak exercise.

Supine and sitting blood pressures and maximal systolic pressures were related to body size and age in children with BSA < 1 m² (table 5). In males with BSA ≥ 1.2 m², supine and sitting blood pressures were also related to body size and age, with systolic pressures affected more by body size than by age. These correlations were negligible in children with BSA 1–1.19 m² and in females with BSA ≥ 1.2 m² (table 5). Except for children with BSA < 1 m², maximal diastolic pressure was weakly related to body size and age in the other three subgroups.

Maximal Systolic Pressure to Maximal Power Output and Resting Systolic Pressures

Maximal systolic pressure was positively related to power output. The coefficients of correlation between maximal systolic pressure and maximal power output were 0.69 in children with BSA < 1 m², 0.58 in children with BSA 1–1.19 m², 0.80 in males with BSA ≥ 1.2 m² and 0.63 in females with BSA ≥ 1.2 m²

TABLE 3. *Descriptive Data Stratified by Height in Males with Body Surface Area ≥ 1.2 m² (Exercise Program III)*

Height (m)	No. of subjects		Weight (kg)	BSA (m²)	Age (years)	Total work (kg-m)	Mean power (kg-m/min)
< 1.50	7	Mean	36	1.22	10	2986	420
		SD	2	0.03	1	344	24
		Min	34	1.20	9	2500	385
		Max	41	1.26	13	3500	484
1.50–1.59	13	Mean	44	1.37	12	4885	516
		SD	6	0.08	1	1627	72
		Min	37	1.26	10	2900	414
		Max	54	1.49	14	8100	648
1.60–1.69	10	Mean	58	1.63	14	11225	729
		SD	9	0.11	4	4990	148
		Min	44	1.43	13	4100	482
		Max	73	1.82	18	19300	941
1.70–1.79	20	Mean	68	1.82	20	15448	848
		SD	6	0.08	6	4676	112
		Min	59	1.72	14	7250	620
		Max	86	2.02	33	23250	1024
≥ 1.80	20	Mean	76	1.99	18	13835	806
		SD	11	0.14	4	4747	127
		Min	62	1.82	14	5000	526
		Max	110	2.37	29	21900	995

Abbreviations: BSA = body surface area; DP = diastolic pressure; ET = exercise time; HR = heart rate; MAX PWR = maximal power output; Min, Max = minimal, maximal values; SP = systolic pressure.

(table 6). Maximal systolic pressure was also related to the level of resting systolic pressure in that those with the highest supine or sitting pressure tended to have high values for maximal systolic pressure during exercise (table 6). This finding was primarily seen in children with BSA < 1 m² or BSA 1–1.19 m² and in males with BSA ≥ 1.2 m² (table 6).

Exercise Electrocardiogram

ST-segment depression of 1–2 mm was observed in 12.1% (18 of 149) of the population at peak exercise. These ST-segment changes occurred in eight of 90 males and in 10 of 59 females ($p > 0.1$) (table 7). The frequency of ST depression within each of the four subgroups was 12% in children with BSA < 1 m², 25% in children with BSA 1–1.19 m², 7% in males with BSA ≥ 1.2 m² and 13% in females with BSA ≥ 1.2 m².

Twelve of 18 subjects (67%) with ST depression ≥ 1 mm had it in at least V_5 (table 7). Ten (56%) of the 18 subjects had ST depression ≥ 1 mm in lead V_5 only. In these 10 subjects, the averages for J-point displacement, ST depression and slope of the ST segment in six males were −1.5 mm, −1.2 mm and +2.9 mV/sec and in four females −1.6 mm, −1.1 mm and +2.4 mm, respectively. Eight (44%) of 18 subjects had ST depression ≥ 1 mm in the left precordial leads and in at least one or more of the inferior electrocardiographic leads (2, 3, aV_F and Frank lead Y); six (33%) had the finding in the inferior leads only.

Fifteen subjects had ST depression that was < 1 mm (average −0.5 mm) below the baseline in the left precordial leads (V_5, V_6 and Frank lead X). In these subjects, the average ST depression was −0.5 mm in seven females and −0.4 mm in eight males. The average isolated J-point depression without ST depression below the baseline was −1.2 mm in 67 subjects, of which −1.1 mm occurred in 31 males and −1.3 mm in 36 females. These results represent the average maximal J-point depression (according to sex) from one of three leads (V_5, V_6 or Frank lead X) in each of 67 subjects. J-point depression more than 1 mm below the baseline was not observed in the anterior leads V_{1-4}.

Recovery Period

All postexercise data were recorded with the subject in the supine position. The average heart rates at 1 minute after exercise were 122 beats/min in children with BSA < 1 m² (exercise program I), 129 beats/min in children with BSA 1–1.19 m² (exercise program II), 135 beats/min in males and 149 beats/min in females with BSA ≥ 1.2 m² (exercise program III). The

TABLE 3. (*Continued*)

MAX PWR (kg-m/min)	ET (min)	Blood pressures and heart rates: Supine HR (beats/min)	Supine SP (mm Hg)	Supine DP (mm Hg)	Sitting HR (beats/min)	Sitting SP (mm Hg)	Sitting DP (mm Hg)	Maximal HR (beats/min)	Maximal SP (mm Hg)	Maximal DP (mm Hg)
629	7.1	78	105	68	81	105	73	187	142	83
160	0.4	9	5	7	37	6	7	15	16	15
500	6.5	60	98	58	80	98	58	160	128	60
800	7.7	88	110	80	100	112	80	188	172	100
800	9.3	77	110	66	86	112	73	189	156	82
158	1.7	15	8	7	16	8	11	15	15	8
500	7.2	60	92	50	55	60	60	166	134	70
1000	12.5	100	122	76	100	124	100	220	192	98
1180	14.7	75	114	70	74	120	79	193	178	77
274	3.9	20	7	6	15	14	11	11	26	14
800	8.5	49	106	60	53	106	70	176	154	58
1600	20.5	120	126	80	100	154	102	214	234	100
1390	16.8	72	121	70	82	126	80	199	199	71
220	4.4	9	11	9	14	12	13	11	23	19
1200	11.2	53	102	54	59	110	52	176	166	46
1800	22.7	80	142	86	100	146	102	220	238	94
1320	16.7	72	124	73	83	124	73	196	200	80
246	3.4	15	8	10	18	8	10	16	21	15
800	9.5	41	108	38	48	108	38	150	174	40
1800	22.0	100	136	84	120	136	84	220	254	98

average heart rate 20 minutes after exercise for each of the four subgroups was 87–103 beats/min.

The systolic pressure gradually returned to the preexercise level in all subgroups within 10 minutes after peak effort. In a few subjects, the immediate postexercise systolic pressure exceeded the maximal systolic pressure level by 5–20 mm Hg and then returned gradually to the preexercise level. The diastolic pressures returned promptly to the preexercise level after cessation of the exercise test.

ST-segment depression ≥ 1 mm in the 18 subjects rapidly regressed to the preexercise level after the cessation of strenuous exercise and was not associated with symptoms. In 20% of these subjects, complete recovery of the J point and ST segments to the preexercise level did not occur until approximately 10 minutes after exercise. Rhythm or conduction disturbances during exercise testing were rare in this population, which did not have previous documentation of cardiac arrhythmia.

Discussion

This study provides clinical data on total work, work rate, blood pressure, heart rate and associated electrocardiographic responses in normal subjects who perform an exhaustive amount of exercise in a continuous, progressive bicycle protocol. The three exercise programs in this protocol are appropriate for clinical testing of growing subjects who vary in body size and physical capability.

The longest exercise time in this study was 22.7 minutes, in a male who was 1.78 meters tall. The shortest exercise time was 2.5 minutes, in a boy who was 1.08 m tall. These exercise times correspond to a maximal range of 1600 kg-m/min for maximal power output and 3.3 l/min for estimated peak $\dot{V}O_2$.[22] None of the subjects complained of boredom because of a long exercise time or lack of physical challenge during the exercise test. The distribution of the total exercise times in our population using the bicycle protocol permits several tests each day, which is a practical consideration in the clinical laboratory.

Total Work and Power Output

Several investigators[13, 14] have attempted to measure working capacity in different subjects and to use this variable to discriminate between normals and those with different diseases of varying severity. The use of the PWC_{170} test[13] to estimate working capacity by determining the highest rate of work (power output) at which the pulse and respiratory rates do not exceed 170 beats/min and 30 breaths/min, respectively, during continuous, progressive bicycle exercise, is not without some concern. Many children can exceed and maintain for various time periods a higher heart rate than 170 beats/min. Their cardiac output, oxygen up-

TABLE 4. *Descriptive Data Stratified by Height in Females with Body Surface Area ≥ 1.2 m² (Exercise Program III)*

Height (m)	No. of subjects		Weight (kg)	BSA (m²)	Age (years)	Total work (kg-m)	Mean power (kg-m/min)
< 1.60	10	Mean	48	1.43	13	3865	463
		SD	6	0.09	3	1628	81
		Min	39	1.30	10	2100	403
		Max	57	1.58	17	7500	625
1.60–1.69	19	Mean	59	1.63	17	6218	572
		SD	9	0.12	3	1970	83
		Min	48	1.48	12	2900	414
		Max	84	1.94	23	9300	689
≥ 1.70	9	Mean	61	1.73	19	9622	684
		SD	5	0.07	4	4510	135
		Min	53	1.62	13	5500	550
		Max	69	1.79	24	17300	901

Abbreviations: BSA = body surface area; DP = diastolic pressure; ET = exercise time; HR = heart rate; MAX PWR = maximal power output; Min, Max = minimal, maximal values; SP = systolic pressure.

take, heart rate and blood pressure continue to increase with progressive changes in power output.[26, 27] Also, some children with cardiac disease may have difficulty reaching a heart rate of 170 beats/min during exercise because of a disturbance in cardiac rate and rhythm or signs and symptoms of distress.[1, 28] These factors present some difficulties in using this method for estimating working capacity in children.

Goldberg et al.[14] estimated working capacity in normal children and those with cardiac disease using exhaustion as an end point for the exercise procedure. The work load (in kg-m/min) that produced a heart rate of 170 beats/min was determined and reported as a percent of normal. Goldberg et al. reported low exercise pulse rates and endurance in children with cardiac disease. In contrast, Cumming[29] reported normal mean maximal heart rate and endurance times from treadmill exercise above the tenth percentile of normal in 79% of children with cardiac defects. This author concluded that maximal exercise tests for estimating exercise capacity may not distinguish between children with mild or severe heart disease.

Cumming et al.[30] have used total exercise time on the treadmill as an index of exercise capacity or endurance in normal children. In this report[30] the exercise data were stratified by age and sex without major

TABLE 5. *Coefficients of Correlation Between Body Size, Age and Exercise Data in Normal Subjects*

Exercise program		Total work	Mean power output	Maximal power output	Blood pressures: Supine S	Supine D	Sitting S	Sitting D	Maximal S	Maximal D
I (BSA < 1 m²) Males and females	Ht (m)	0.82	0.82	0.82	0.48	0.44	0.43	0.42	0.48	0.49
	Wt (kg)	0.68	0.69	0.73	0.54	0.63	0.68	0.50	0.49	0.25
	BSA (m²)	0.81	0.81	0.84	0.55	0.57	0.59	0.49	0.52	0.40
	Age (years)	0.66	0.67	0.65	0.57	0.40	0.56	0.13	0.41	0.37
II (BSA 1–1.19 m²) Males and females	Ht (m)	0.10	0.13	0.12	0.40	0.40	0.15	0.30	0.04	−0.07
	Wt (kg)	0.08	0.08	0.12	0.04	0.15	0.17	0.20	0.05	0.09
	BSA (m²)	0.15	0.20	0.21	0.26	0.35	0.14	0.38	0.07	0.06
	Age (years)	0.13	0.15	0.18	0.28	0.37	0.22	0.34	0.07	0.03
III (BSA ≥ 1.2 m²) Males	Ht (m)	0.72	0.76	0.74	0.64	0.30	0.58	0.31	0.73	−0.15
	Wt (kg)	0.72	0.76	0.77	0.61	0.35	0.57	0.27	0.75	−0.09
	BSA (m²)	0.76	0.78	0.78	0.64	0.34	0.60	0.28	0.76	−0.10
	Age (years)	0.53	0.55	0.56	0.37	0.25	0.34	0.23	0.52	0.03
III (BSA ≥ 1.2 m²) Females	Ht (m)	0.60	0.62	0.63	−0.12	−0.14	−0.02	0.26	0.41	0.02
	Wt (kg)	0.38	0.16	0.32	−0.14	−0.05	−0.04	0.07	0.22	0.04
	BSA (m²)	0.48	0.25	0.43	−0.16	0.01	−0.04	0.15	0.31	0.05
	Age (years)	0.20	0.13	0.17	0.14	0.05	0.06	0.15	0.15	0.28

Abbreviations: BSA = body surface area; Ht = height; Wt = weight; S, D = systolic, diastolic.

TABLE 4. (*Continued*)

MAX PWR (kg-m/min)	ET (min)	Blood pressures and heart rates: Supine HR (beats/min)	Supine SP (mm Hg)	Supine DP (mm Hg)	Sitting HR (beats/min)	Sitting SP (mm Hg)	Sitting DP (mm Hg)	Maximal HR (beats/min)	Maximal SP (mm Hg)	Maximal DP (mm Hg)
670	8.1	96	119	71	103	120	74	198	160	84
189	1.8	18	8	7	19	9	7	20	14	10
500	6.7	70	106	55	75	108	60	158	144	64
1000	12.0	120	132	78	120	132	82	220	182	98
910	10.6	83	118	72	93	120	78	199	170	88
166	2.0	20	9	7	18	11	9	10	20	8
500	7.0	52	108	62	61	104	60	180	134	66
1200	13.5	120	132	80	140	134	90	220	202	102
1089	13.4	77	115	70	86	119	80	197	181	85
247	3.6	18	7	9	17	8	6	13	23	8
800	10.0	46	108	56	61	102	74	176	154	74
1400	19.2	102	132	82	120	126	90	220	232	98

attention to the effect of body size on exercise endurance. Our data reflect the influence of sex and growth on the ability to perform in the protocol. There were no significant differences in physical work between the boys and girls with BSA < 1 m^2 and those with BSA 1–1.19 m^2. As a result, the boys and girls within these subgroups were combined because of sample size. In those subjects with BSA ≥ 1.2 m^2, the mean values for total work, mean and maximal power outputs in the females were significantly lower than in the males ($p < 0.01$). Therefore, these data were separated by sex.

Since body size affected the units of work more than age, we chose to stratify our data by height. Height accounted for up to 67% of the variation for total work, up to 58% for mean and up to 38% for maximal power output in three subgroups: children with BSA < 1 m^2 and males and females with BSA ≥ 1.2 m^2. In normal subjects this index of body size (height) reflects the growth process, demonstrated by a positive relationship to increasing leg length,[31] leg muscle mass[31] and cardiac volume.[32] These factors are related to an increasing maximal oxygen transport, oxygen utilization and working capacity in children.

When interpreting the units of work from our bicycle protocol, it is important to know which exercise program was used for testing. The absolute values for total work and rate of work at peak performance differ according to the exercise program. These values can be used to assess current work capacity and to determine the changes during growth and after interventions, i.e., physical training and medical and surgical treatment of subjects with cardiovascular disease.

During controlled effort, a subject is usually at or near the mean $\dot{V}O_2$ demand[22] for a given work load after working at the level for 1.5 minutes or more (unpublished data). This criterion of 1.5 minutes is used in this study for determining the highest work rate (maximal power output) for subjects during a continuous protocol. It is reasonable, therefore, that maximal power output can be used to estimate peak

TABLE 6. *Coefficients of Correlation Between Maximal Systolic Pressure and Resting Blood Pressure and Maximal Power Output in Normals*

Exercise program		Blood pressures: Supine S	Supine D	Sitting S	Sitting D	Maximal power output
I (BSA < 1 m^2) Males and females	MSP	0.67	0.44	0.51	0.47	0.69
II (BSA 1–1.19 m^2) Males and females	MSP	0.32	0.06	0.41	0.56	0.58
III (BSA ≥ 1.2 m^2) Males	MSP	0.67	0.23	0.72	0.33	0.80
III (BSA ≥ 1.2 m^2) Females	MSP	0.13	−0.25	0.18	0.06	0.63

Abbreviations: BSA = body surface area; MSP = maximal systolic pressure; S, D = systolic, diastolic.

TABLE 7. *Descriptive Data in Normal Subjects with ST Depression During Exhaustive Exercise*

Height (m)	Sex	Age (years)	BSA (m^2)	Heart rate (beats/min)		Blood pressure (mm Hg)		ST depression (mm) according to electrocardiographic leads			
				Sitting	Maximal	Sitting	Maximal	V_5	V_6	X	2, 3, aV_F or Y
BSA < 1 m^2											
1.13	F	8	0.80	120	200	98/46	110/60			1.0	
1.24	F	8	0.86	75	188	98/74	136/86				1.0
BSA 1 – 1.19 m^2											
1.26	F	6	1.09	70	176	110/66	134/72			1.0	1.0
1.33	M	10	1.05	73	170	102/68	138/76	1.2	1.0		1.0
1.35	M	8	1.01	100	200	96/62	142/78	1.0	1.0		
1.37	F	9	1.06	100	180	124/80	180/70	1.0			
1.41	M	11	1.11	70	188	108/68	148/16	1.1			
1.45	F	14	1.14	120	200	108/82	142/90	1.0			
BSA ≥ 1.2 m^2											
1.46	M	10	1.22	100	200	98/72	150/100	1.0			
1.55	M	14	1.30	100	180	120/70	156/78	2.0			
1.57	M	12	1.54	86	174	110/60	170/86	1.0			
1.70	M	20	1.75	100	200	120/80	190/74				1.0
1.77	M	21	1.84	87	200	122/80	178/74				1.5
BSA ≥ 1.2 m^2											
1.52	F	17	1.52	120	214	122/72	166/90				1.0
1.55	F	12	1.53	120	200	132/82	150/88	1.5			
1.59	F	17	1.58	100	180	108/76	146/84	1.0			
1.73	F	13	1.62	61	182	120/76	174/74				1.0
1.79	F	20	1.79	94	176	126/82	174/88				1.0

Abbreviation: BSA = body surface area.

aerobic power (maximal oxygen uptake) when the direct measurement of oxygen uptake is unavailable. For example, the highest maximal power output in the females is 1400 kg-m/min (table 4), which corresponds to an estimated peak aerobic power (maximal oxygen uptake) of 3.13 l/min.[22]

Blood Pressure

Blood pressure measurements were possible in all subjects with the programmed electrosphygmomanometer (tables 2, 3 and 4). With the air compression cuff and microphone in proper position, the Korotkoff sounds were easily audible and distinguishable from artifact, even in the small child.

In this study, the technique reveals a maximal systolic pressure range of 150 mm Hg, with the upper and lower 2.5% of the total population having maximal systolic pressures of 234–254 mm Hg and 104–108 mm Hg, respectively. Maximal systolic pressure is related to maximal power output and absolute levels of resting systolic pressure. It is reasonable that this rise in systolic pressure during peak effort is the result of interplay between stroke volume, systemic vascular resistance and duration of left ventricular ejection.

The relationships of blood pressure to body size and age are best observed in children (BSA < 1 m^2) and males (BSA ≥ 1.2 m^2), with the systolic pressure to body size stronger than to age in the latter group. Voors et al.[33] reported that height and height/weight[3] have a strong influence on resting blood pressure. Our data revealed a strong influence of body size and age on maximal systolic pressure in children (BSA < 1 m^2) and a strong influence of body size primarily on maximal systolic pressure in males and females with BSA ≥ 1.2 m^2.

Exercise Electrocardiogram

ST-segment depression ≥ 1 mm was recorded during exhaustive exercise in 12.1% (18 of 149) of a normolipemic population, with a frequency of 8.9% in males and 16.9% in females. In these 18 subjects, there was no sign of vasoregulatory abnormality[34] during the preexercise period. The frequencies of exercise-induced ST depression are similar to our previous report[16] of 7.3% in males and 14.6% in females, and also parallel the findings in adult males and females.[35, 36] The high percentage of ST depression ≥ 1 mm persists in the females with BSA ≥ 1.2 m^2 (13.2%), compared with the males with BSA ≥ 1.2 m^2 (7%). Eight of the 18 patients (44%) had ST-segment changes in the inferior leads; 63% of the changes occurred in females and 37% in males. A similar sexual difference for ST depression in the inferior leads was reported by Sketch et al.[37] in an evaluation of adults for coronary artery disease.

The mechanism of the ST-segment changes in this population, including the different frequencies of ST depression according to sex and size, is unclear. Postexertional ST depression has been reported in adults with elevated systolic pressure during exercise.[38, 39] In our study, with one exception, the peak systolic pressures during exercise in the 18 subjects with ST depression ≥ 1 mm were not appreciably elevated compared with the mean for the members in the height class (table 7). Our study also differs from the reported adult series in that the ST depression occurred during peak exercise and resolved immediately after exercise.

Mirvis et al.[40] recorded maximal junctional depression along the lower left sternal border during supine exercise with the application of 42 left anterior precordial electrodes in 15 normal males younger than 35 years of age. These authors constructed exercise maps suggesting that the junctional depression was due to competition between two electrophysiologic processes, i.e., normal repolarization and delayed terminal depolarization of the myocardium during stress.

This explanation may, in part, apply to some of the findings in our study. However, the ST depression and junctional depression occurred in leads V_5, V_6, lead X and/or the inferior leads and not in the precordial leads along or close to the left sternal border. Moreover, our data suggest that sex and size influence the frequency of exercise-induced ST depression of 1 mm or more.

We cannot conclude from our data that the ST depression ≥ 1 mm recorded in the 18 subjects during maximal physical exertion indicates an increased release of potassium from the myocardial cell,[40] because oxygen demand exceeded oxygen supply or the presence of covert ischemic heart disease.

An ST-segment change during exercise does not confirm the presence or absence of cardiac disease. It appears that ST depression of 1 mm during exercise in a child with a normal physical examination including blood pressure and blood lipids, has a low probability of reflecting ischemia due to cardiovascular disease and is of minor clinical importance. On the other hand, ST depression of 1 mm or more during exercise in a child with signs of cardiovascular disease or elevated blood lipids, or the occurrence of ST depression > 2 mm during exercise without an obviously abnormal physical examination, has a high probability of reflecting ischemia due to the presence and severity of cardiovascular disease.

Our data further indicate that the recording of several electrocardiographic leads for the detection and distribution of ST depression and for the evaluation of cardiac arrhythmia is superior to single-lead recordings. The approach seems reasonable, especially in the evaluation of acquired and congenital heart lesions that may occur with malposition and include several anatomic abnormalities affecting the right and left sides of the heart that may cause significant ST depression.[28]

Exercise Testing and Recording Multiple Variables

Recording a single variable such as exercise capacity is insufficient for a comprehensive evaluation using exercise tests. Some children with cardiovascular disease may have normal tolerance for exercise but develop abnormal blood pressures and ECGs during active exercise. A decreased tolerance for exercise or an exaggerated heart rate, blood pressure and electrocardiographic response with low exercise tolerance in a young subject without overt cardiac disease should stimulate further investigation to detect pulmonary or vascular abnormalities and to assess the level of physical fitness. The yield of relevant information from exercise testing will increase if the adaptive responses to exercise are monitored and compared with normal values. Clinical criteria for normal systolic pressure responses and estimates of working capacity from bicycle exercise testing in growing subjects should be based on normal data derived from body size rather than from age.

Reproducibility of Exercise Testing

The average differences of the follow-up test from the initial test was + 100 kg-m for total work, + 6 mm Hg for systolic and + 8 mm Hg for diastolic pressures, and −4 beats/min for heart rate with similar electrocardiographic changes. These differences were not statistically significant. All subjects repeated the signs associated with exhaustive exercise during the initial study.

Supervising Maximal Exercise Tests

It appears that controlled exercise tests can be performed in the pediatric age group without major difficulties.[1, 12, 14, 21, 22, 27, 29, 30, 32] Our laboratory has not experienced any medical emergencies associated with exercise testing in children with a variety of problems of varying severity. However, there is a need for a proper assessment of the risk of exercise testing in the pediatric age population. All of the exercise tests in this study were conducted by a physician. This approach was especially useful in properly timing and coordinating the recordings of multiple variables while obtaining peak performance from each subject during the exercise test. When exercise tests are conducted only to assess exercise capacity or to record the ECG, these responsibilities may be delegated to skilled personnel with a physician immediately available in case of emergency.[29, 30]

Acknowledgment

We thank Andrew McDaniels for the computer programming, Vera Naylor and Magdalen A. Anyaegbu for technical assistance, and Margaret DeHo for typing the manuscript.

References

1. James FW: Exercise testing in children and young adults: an overview. *In* Cardiovascular Clinics, Exercise and the Heart, edited by Wenger NK. Philadelphia, FA Davis, 1978, pp 187–203
2. Chawla K, Serratto M, Cruz J, Chuquimia R, Miller R, Hastrieter A, Towne WD: Response to maximal and submaximal exercise testing in patients with congenital complete heart block. (abstr) Circulation **56** (suppl III): III-171, 1977
3. Rozanski JJ, Dimich I, Steinfeld L, Kupersmith J: Maximal exercise stress testing in evaluation of arrhythmias in children: results and reproducibility. Am J Cardiol **43**: 951, 1979
4. James FW, Kaplan S, Schwartz DC, Sandker MJ, Naylor VN: Response to exercise in patients after total surgical correction of tetralogy of Fallot. Circulation **54**: 671, 1976
5. Kalloran KH: The telemetered exercise electrocardiogram in congenital aortic stenosis. Pediatrics **47**: 31, 1971
6. Connor TM: Evaluation of persistent coarctation of aorta after surgery with blood pressure measurement and exercise testing. Am J Cardiol **43**: 74, 1979
7. James FW, Kaplan S: Spectrum of exercise responses in children with aortic stenosis. (abstr) Pediatr Res **11**: 393, 1977
8. James FW, Kaplan S: Systolic hypertension during submaximal exercise after correction of coarctation of the aorta. Circulation **50** (suppl II): II-34, 1974
9. James FW, Donner R, Kaplan S: Exercise responses in children with progressive aortic regurgitation. (abstr) Am J Cardiol **41**: 389, 1978
10. Rocchini A, Fred M, Rosenthal A: Detection of arrhythmias in childhood: use of treadmill and dynamic ECG. (abstr) Pediatr Res **11**: 399, 1977
11. Riopel DA, Hohn AR: Age effect on treadmill blood pressure responses in aortic stenosis. (abstr) Pediatr Res **11**: 399, 1977
12. Chandramouli B, Ehmke DA, Lauer RM: Exercise-induced electrocardiographic changes in children with congenital aortic stenosis. J Pediatr **87**: 725, 1975
13. Wahlund H: Determination of the physical working capacity. Acta Med Scand (suppl) **215**: 5, 1948
14. Goldberg SJ, Weiss R, Adams FH: A comparison of the maximal endurance of normal children and patients with congenital cardiac disease. J Pediatr **69**: 46, 1966
15. Godfrey S, Davies CTM, Wozniak E, Barnes CA: Cardiorespiratory response to exercise in normal children. Clin Sci **40**: 419, 1971
16. James FW, Glueck CJ, Fallat RW, Millet F, Kaplan S: Maximal exercise stress testing in normal and hyperlipidemic children. Atherosclerosis **25**: 85, 1976
17. Londe S: Blood pressure in children as determined under office conditions. Clin Pediatr **5**: 71, 1966
18. Masland RP Jr, Heald FP, Goodale WT, Gallagher JR: Hypertensive vascular disease in adolescence. N Engl J Med **255**: 894, 1956
19. Blumenthal S, Epps RP, Heavenrich R, Lauer RM, Lieberman E, Mirkin B, Mitchell SC, Naito VB, O'Hare D, Smith WM, Tarazi RC, Upson D: Report of the task force on blood pressure control in children. Pediatrics **59** (suppl): 797, 1977
20. Report of the Joint National Committee: Detection, Evaluation and Treatment of High Blood Pressure. US Department of Health, Education and Welfare, Public Health Service, National Institutes of Health
21. Adams FH, Linde LM, Miyake H: The physical working capacity of normal school children. Pediatrics **28**: 55, 1961
22. Bengtsson E: The working capacity in normal children evaluated by submaximal exercise on the bicycle ergometer and compared with adults. Acta Med Scand **154**: 91, 1956
23. VanBergen FH, Weatherhead DS, Treloar AE, Dobkin AB, Buckley JJ: Comparison of indirect and direct methods of measuring arterial blood pressure. Circulation **10**: 481, 1954
24. Snedecor GW, Cochran WG: Statistical Methods, 6th ed. Ames, Iowa, Iowa State University Press, 1976, p 172
25. Snedecor GW, Cochran WG: Statistical Methods, 6th ed. Ames, Iowa, Iowa State University Press, 1976, p 199
26. Eriksson BO: Cardiac output during exercise in pubertal boys. Acta Paediat Scand **217** (suppl): 53, 1971
27. Strong WB, Miller MD, Striplin M, Salehbhaim: Blood pressure response to isometric and dynamic exercise in healthy black children. Am J Dis Child **132**: 587, 1978
28. James FW: Exercise ECG test in children. *In* Exercise Electrocardiography-Practical Approach, edited by Chung EK. Baltimore, Williams and Wilkins Co, 1979, p 122
29. Cumming GR: Maximal exercise capacity of children with heart defects. Am J Cardiol **42**: 613, 1978
30. Cumming GR, Everatt D, Hastman L: Bruce treadmill test in children: normal values in a clinic population. Am J Cardiol **41**: 69, 1978
31. Vaughan VC III: Growth and Development. *In* Nelson Textbook of Pediatrics, 10th ed., edited by Vaughan VC III, McKay RJ. Philadelphia, WB Saunders Company, 1975, pp 13–51
32. Bouchard C, Malina RM, Hallmann W, Leblanc C: Submaximal working capacity, heart size and body size in boys 8–18 years. Eur J Appl Physiol **36**: 115, 1977
33. Voors AW, Webber LS, Frerichs RR, Berenson GS: Body height and body mass as determinants of basal blood pressure in children — the Bogalusa Heart Study. Am J Epidemiol **106**: 101, 1977
34. Friesinger GC, Biern RO, Liker I, Mason RE: Exercise electrocardiography and vasoregulatory abnormalities. Am J Cardiol **30**: 733, 1972
35. Astrand I: Exercise electrocardiograms recorded twice with an 8 year interval in a group of 204 women and men 48–63 years old. Acta Med Scand **178**: 27, 1965
36. Cumming GR, Dufresne C, Kich L, Samm J: Exercise electrocardiogram patterns in normal women. Br Heart J **35**: 1055, 1973
37. Sketch MH, Mohiuddin SM, Lynch JD, Zencka AE, Runco V: Significant sex differences in the correlation of electrocardiographic exercise testing and coronary arteriograms. Am J Cardiol **36**: 169, 1975
38. Kusumi F, Bruce RA, Ross MA, Trimble S, Voegt AE: Elevated arterial pressure and postexertional ST segment depression in middle-aged women. Am Heart J **92**: 576, 1976
39. Chiang BN, Alexander R, Bruce RA, Thompson DJ, Ting N: Factors related to ST segment depression after exercise in middle aged Chinese men. Circulation **40**: 315, 1969
40. Mirvis DM, Keller FW Jr, Cox JW Jr, Zettergren DG, Dowdre RF, Ideker RE: Left precordial isopotential mapping during supine exercise. Circulation **56**: 245, 1977
41. Case RB, Nasser MG, Crampton RS: Biochemical aspects of early myocardial ischemia. Am J Cardiol **24**: 766, 1969