Cardiopulmonary Exercise Testing in Children*

An Individualized Protocol for Workload Increase

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Objectives: To investigate the feasibility of individualized workload increments, as used in adults, for exercise testing in children; and to investigate whether this individualized protocol makes it possible to satisfy the usual criteria for maximal exercise (clinical exhaustion, predicted maximum heart rate [HRmax], oxygen uptake [VO₂] plateau, maximal respiratory exchange ratio > 1.1).

Design: Prospective clinical study.

Setting: Pediatric exercise testing laboratory.

Subjects: Ninety-two children aged 5 to 17 years with various cardiac and respiratory diseases (33 with asthma, 11 with bronchopulmonary dysplasia, 6 with cystic fibrosis, 10 with congenital heart disease, and 32 miscellaneous).

Interventions: Individualized maximal incremental exercise testing. The increase in workload was adapted to the individual and was calculated from predicted maximal oxygen uptake (VO₂max) for each child. The test lasted 10 to 12 min.

Results: The exercise test was well tolerated by all children and was maximal in all but seven patients. A total of 65.7% of children reached the predicted VO₂max and 68.4% satisfied the criteria for a VO₂ plateau at peak exercise. The predicted HRmax was achieved in all but two children. The mean maximal respiratory exchange ratio was 1.06.

Conclusion: The individualized protocol for increasing workload, based on VO₂ rather than power, was well tolerated by children. In our view, the best two criteria for assessing the maximality of the tests were clinical exhaustion and HRmax, especially if the VO₂ plateau was not reached. These results suggest that individualized protocols could be used instead of standardized tests for exercise testing in children.

Key words: children; exercise testing; individualized workload

Abbreviations: HR = heart rate; HRmax = maximum heart rate; RER = respiratory exchange ratio; RERmax = maximal respiratory exchange ratio; VO₂ = oxygen uptake; VO₂max = maximal oxygen uptake; Wmax = maximum watts

Exercise tests are widely used as diagnostic and therapeutic tests in adults. These dynamic tests evaluate exercise tolerance and adaptations, essentially cardiorespiratory in nature. They are also useful for diagnosis and assessment of abnormal symptoms during exercise, and for initiation and individualization of exercise training.

The methodology of exercise tests has largely been described, and there are many protocols for use in adults. Maximum oxygen uptake (VO₂max) is widely recognized to be the best single index of aerobic fitness. Its measurement requires the patient to achieve maximal exercise. However, the criteria for maximal exercise described in adults are rarely satisfied in children. No criterion specific for children has been precisely described. Results obtained with small numbers of children have shown that various ventilation and cardiac variables (such as ventilation, respiratory exchange ratio [RER], respiratory rate, oxygen pulse, heart rate [HR]) measured during exercise tests have maximal values in children that are very different from those in adults.

An individualized methodologic approach to exercise testing has been used in adult patients with pulmonary diseases. In this case, the maximum workload and the increase in load during the test are adapted to each individual. Could this individualized approach be extended to children? Would it be tolerated by children?
This prospective study was carried out in our pediatric pulmonary function laboratory from February 1997 to February 1999, and focused on the methodology used for the tests performed. Its principal aim was to investigate the feasibility of an individualized methodology for exercise testing in ill children. Moreover, we investigated whether this approach makes it possible to satisfy the criteria for maximal exercise generally required in adults.

**Materials and Methods**

*Subjects*

Between February 1997 and February 1999, exercise tests were carried out in 92 children presenting with various diseases (Table 1). The tests were carried out for clinical reasons: (1) assessment of exercise tolerance; (2) diagnosis and confirmation of abnormal symptoms during exercise (eg, dyspnea, thoracic pain, malaise, urticaria); (3) assessment of impairments and specific adaptations to exercise in children suffering from chronic diseases, such as cystic fibrosis, asthma, congenital heart disease (this evaluation is often obligatory before authorization is given to participate in sports); and (4) monitoring of the progression of a disease or evaluation of the efficacy of treatment (oxygen uptake \( \dot{V}O_2 \)) being a reproducible, quantifiable index.

The mean (± SD) age of our population (56 boys and 36 girls) was 12 ± 3.04 years (range, 5 to 17 years). Fifty-five of the children (59.7%) were prepubertal.

*Materials*

The exercise tests were performed on a cycle ergometer with an electromagnetic braking (Lode BV; Groningen, The Netherlands) or a motor-driven treadmill (Marquette Electronics; Milwaukee, WI). The choice of ergometer depended on the height of the child (minimum height of 125 cm for the cycle), the indication for the exercise test, and, in some cases, the preferences of the child. The cycle ergometer was used most frequently because it facilitated an increase in load and the monitoring of clinical parameters with a 12-lead ECG (Marquette Max-1; Marquette Electronics), oxygen saturation by pulse oximetry (Ohmeda 3700; Ohmeda; Louisville, CO), and BP.

Respiratory exchange was measured over three respiratory cycles, using a mixing chamber with a variable volume (Gould 9000; Sensoromedics; Dayton, OH). Children wore a nose clip and breathed through a mouthpiece attached to a low-resistance valve (large 2700 valve; Hans Rudolph; Kansas City, MO) with 100 mL of dead space. On the expiratory side, this apparatus was connected via large tubing (internal diameter of 3.5 cm) to a pneumotachograph located at the entrance of the mixing chamber, for flow measurement. Gas samples were taken from the mixing chamber over three respiratory cycles and were analyzed using an infrared analyzer for carbon dioxide and a paramagnetic analyzer for oxygen.

Mean values for \( \dot{V}O_2 \), carbon dioxide output, RER, and minute ventilation were calculated over 20-s intervals. The system was calibrated prior to each individual test using standard gas mixtures of known oxygen and carbon dioxide content.

*Protocol*

This study was carried out in the Pulmonary Function Laboratory of the Pediatric Pneumology Department of Necker Enfants-Malades Hospital (Paris, France). The same protocol was used for all 92 patients. A pediatric pulmonologist and an experienced technician observed the children during the exercise test and watched for excessive stress (eg, severe wheezing, chest pain, lack of coordination) or adverse signs (eg, ECG abnormalities, falling BP, large decrease in oxygen saturation). Resuscitation equipment and a defibrillator were always available during tests.

A 12-lead ECG and spirometry were first carried out at rest, making it possible to calculate the predicted maximum ventilation of the child, as FEV\(_1\) × 35. The test procedure was then explained to the child.

**Individualized Protocol for Workload Increase**

The exercise test was a progressive incremental test. The increase in workload was individualized for each child, as previously described for adults. Individualization was based on the predicted \( \dot{V}O_2\)max of each child, converted into maximum watts (Wmax), to make it easier to increase the load (in watts) during the test.

Basal \( \dot{V}O_2 \) was calculated as (height in centimeters × 2) – 100, and predicted \( \dot{V}O_2\)max was calculated according to the Wasserman norms as a function of sex, weight, and the age of the child. We then calculated the difference between \( \dot{V}O_2\)max and basal \( \dot{V}O_2 \), Wmax corresponding to this difference was calculated as follows:

\[
Wmax = (\text{predicted } \dot{V}O_2\text{max} - \text{basal } \dot{V}O_2)/10.3,
\]

where 10.3 mL of \( O_2\)min/W is the equivalent in oxygen of each watt. So, we achieved maximal power to reach Wmax.

The total duration of the test was 10 to 12 min. The test involved four consecutive periods: (1) a 3-min to 5-min rest period; (2) a 3-min period of warm-up against a workload corresponding to 20% of the calculated Wmax; and (3) an 8-min exercise period. The remaining 80% of the workload was divided by eight to define the increase in workload for each 1-min stage (Fig 1). Based on clinical evaluation and the experience of the physician, the workload was increased more slowly for the last

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**Table 1—Underlying Diseases**

<table>
<thead>
<tr>
<th>Diseases</th>
<th>No.</th>
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<tbody>
<tr>
<td>Asthma</td>
<td>33</td>
</tr>
<tr>
<td>Spasmodychnic cough</td>
<td>3</td>
</tr>
<tr>
<td>Abnormal symptoms on exercise, essentially exercise dyspnea</td>
<td>10</td>
</tr>
<tr>
<td>Complex congenital heart disease, treated surgery during the first few years of life (tetralogy of Fallot, mitral atresia, pulmonary stenosis, tricuspid atresia)</td>
<td>10</td>
</tr>
<tr>
<td>Cystic fibrosis</td>
<td>6</td>
</tr>
<tr>
<td>Bronchopulmonary dysplasia</td>
<td>10</td>
</tr>
<tr>
<td>Interstitial lung diseases (hemosiderosis, alveolar proteinosis, extrinsic allergic alveolitis, acrolein poisoning)</td>
<td>6</td>
</tr>
<tr>
<td>Miscellaneous (dermatomyositis, scleroderma, scoliosis, malignant neoplasia and hemopathies, hemorrhagic rectocolitis, scimitar syndrome, operated-on double aortic arch, acquired epidermolysis bullosa, venous angiodysplasia)</td>
<td>14</td>
</tr>
</tbody>
</table>
few minutes in some children to prevent muscle limitation, which would have made it necessary to stop the exercise prematurely before maximal exercise was achieved. A recovery period (4), with a workload equivalent to that used for the warm-up period, took at least 2 min, to prevent fainting and to accelerate lactate removal. Finally, there were 3 min of passive recovery.

We manually increased the workload (in watts) directly on the cycle ergometer. The child had to maintain a regular pedaling rhythm of 60 revolutions per min. On the treadmill, once the optimal running speed of the child was reached (mostly between 5 km/h and 6 km/h), only the slope was increased, by 1 to 2% each minute. Optimal running speed was reached during the 3-min warm-up period, as assessed by the testing staff, on the basis of a regular, even-paced run, without large strides, well-matched to treadmill speed, with the child looking comfortable. For each stage, including the warm-up period, speed and gradient were set so as to be equivalent to the preestimated workload in watts.

Throughout the exercise and recovery periods, continuous ECG monitoring was carried out. BP and oxygen saturation were determined at each stage. We allowed the parents to be present throughout the exercise test. They were very curious and wanted to understand the apparatus and the meaning of the measures and results. We asked them to help us to encourage their child to achieve exhaustion during the final stages.

The following criteria for maximal exercise were those used in progressive incremental cardiopulmonary exercise testing in adults,


![Figure 1. Protocol for exercise test: workload incrementation.](image)

...maximal RER (RERmax) of 85% of the predicted value; (3) predicted maximum HR (HRmax) achieved (210 - [0.65 x age]) + 10% (we considered the predicted HRmax to have been achieved if the HR recorded was 90% of the predicted value); and (4) maximal RER (RERmax) of > 1.1 (in adults, the RERmax must be > 1.1. Three of these criteria must be satisfied for maximal exercise to be considered to have been achieved).

We used Student’s t test to compare VO2max values between boys and girls. The χ² test was used to compare the VO2 values obtained from prepubescent and pubescent children; RERmax values in those who had and had not achieved a VO2 plateau, and between children who had and had not reached HRmax; and HRmax values in those who had and had not achieved a VO2 plateau. Statistical significance was defined as p < 0.05.

**RESULTS**

Thirty-seven exercise tests were carried out using a treadmill, and 55 exercise tests were performed using a cycle ergometer. Using this individualized protocol, it was straightforward to perform exercise tests in children aged from 5 to 17 years. No particular complications, especially of cardiac origin, were observed. The children tolerated the protocol well, with the game-like aspects of the apparatus (eg, the helmet and the large number of cables or wires) and the element of challenge being stressed. Maximal tests were not achieved for seven children: three due to an evident lack of motivation of the child and four due to dyspnea or an acute bout of coughing, making it necessary to stop the exercise prematurely.

Predicted VO2max was achieved in 65.7% of patients (62 of 92 tests). If we exclude the seven children for whom the test was not maximal (lack of motivation or dyspnea), 73% of the tests resulted in the predicted VO2max being achieved. The mean VO2max (± SD) measured was 38.1 ± 10.7 mL/kg/min for a mean workload of 127.7 ± 67.7 W. The mean VO2max achieved by the girls was 32.2 ± 7.7 mL/kg/min, whereas that achieved by the boys was 41.3 ± 11.1 mL/kg/min (28.4% difference, p < 0.001).

**Analysis of the Criteria for a Maximal Exercise Test**

In all but the seven tests cited above, complete exhaustion of the subject was achieved. For another nine tests, it appeared that an additional increment in workload would have been supported by the child as clinical exhaustion was not clear. However, for six of the nine tests, a VO2max value at least 90% of the predicted value was achieved.

A VO2 plateau was reached in 63 of the 92 tests (68.4%), and peak VO2 was recorded for the other 29 tests. Sixty-two percent of the children (18 of 29 subjects) for whom peak VO2 was recorded were prepubescent, vs 58.7% (37 of 63 subjects) of those for whom VO2 reached a plateau (not significant, p = 0.76).

Two children with congenital heart disease were receiving negative chronotropic treatment: amiodarone (n = 1) and digoxin (n = 1). In 68 of the other 90 children (75.5%), the predicted HRmax was reached, with a mean value of 191 ± 12.3 beats/min. The 22 children who did not achieve the predicted HRmax included the 7 patients with nonmaximal test results. A HRmax of > 180 beats/min was recorded in 69 of 90 children (76.6%). Twenty-eight children...
had a HRmax of > 200 beats/min (35%). A significant correlation was found between achievement of HRmax and a VO₂ peak (p = 0.02).

The mean RERmax (±SD) was 1.06 ± 0.11 (range, 0.9 to 1.44). This variable was not a decisive criterion for maximal exercise. No significant correlation was found between a RERmax of > 1 and a VO₂ plateau being reached (not significant, p = 0.27) or between a RERmax of > 1 and a HRmax ≥ 90% of the predicted value (not significant, p = 0.27).

**DISCUSSION**

This prospective study, carried out in 92 children suffering from various diseases, demonstrated the feasibility of an individualized protocol for increasing workload during exercise tests. This approach results in a test that is both safe and well tolerated by children. In most cases, the exercise was maximal, although the criteria of maximal exercise generally used in adult populations were not systematically satisfied.

Cardiopulmonary exercise testing with an individualized protocol for increasing workload was feasible in children aged 5 to 17 years, regardless of the ergometer used. The individualized increase in the workload of the exercise was largely responsible for the high level of acceptability of the test to children. In our experience, and as suggested by others, a nonindividualized increase in work, with large increments, may lead to the premature cessation of exercise before cardiac or respiratory limits are reached, due to exhaustion of the muscles of the lower limbs, especially the quadriceps, particularly if the test is carried out with a cycle ergometer. The game-like nature of the apparatus and the challenge of maintaining the speed of pedaling contributed to the acceptability of the protocol. The duration of exercise (10 to 12 min) is sufficiently short not to discourage the child.

Clinical tolerance was good. In the studied population, there were no deleterious events. Cardiac complications (repolarization defects, arrhythmias) are rare in children not suffering from heart disease, and there were only nine children with heart disease in the studied population. Respecting the absolute contraindications (Table 2) for exercise tests limited the risk of cardiovascular problems. These contraindications are rare in children. Fainting, generally a frequent complication, was prevented by the active recovery against a workload equivalent to that used during the warm-up (20% of the maximum workload achieved). Dyspnea was not considered a side effect of exercise, but as an indication of poor adaptation to exercise. At the end or after the exercise test, some asthmatic children had an exercise-induced bronchospasm. This was considered undesirable and led us to modify treatment and to propose a training program to reduce exercise asthma.

The progressive incremental exercise test proposed involves maximal exercise. However, there is some debate about the value of maximal exercise tests. Cooper proposed brief exercise (a few minutes) at constant load, which was thought to be typical of the pattern of physical activity in children. These tests were used for screening and, if the results were abnormal, an incremental maximal exercise test was performed. We believed that for our population of sick children, it was important to assess both aerobic aptitude (exercise tolerance) and adaptations in the various cardiorespiratory parameters measured during the incremental test, and to explain the impairment observed. VO₂max and the ventilatory threshold are the two parameters currently used for aerobic aptitude assessment.

The progressive incremental test proposed herein, with individualization of the increase in workload, is safe and feasible, making it possible to obtain both maximal and submaximal data in a single test. The value of maximal cardiopulmonary exercise tests lies in the definition of these tests itself, “a test making possible an integrated exploration of lung, cardiac and muscular functions... in conditions in which the body makes use of its reserves.” The achievement of a maximum value for VO₂, normally as a plateau, demonstrates the integrated response of all the systems involved in exercise. This test can be used to detect abnormalities that are undetectable during rest or less intensive activities. For example, in bronchopulmonary dysplasia, the correlation between resting function and exercise tolerance has been shown to be weak in some children, we observed hypoxemia only at peak VO₂. Moreover, in our population, it was necessary to achieve maximal exercise for several reasons: (1) to assess objectively (in the safe conditions of a laboratory test) the child’s possibilities in terms of physical activities (and the limits authorized) [this was recently well described

**Table 2—Absolute Contraindications in Adults**

<table>
<thead>
<tr>
<th>Absolute Contraindications in Adults</th>
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<tbody>
<tr>
<td>Myocardial infarction within the previous week</td>
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<tr>
<td>Severe arrhythmia</td>
</tr>
<tr>
<td>Acute febrile illness</td>
</tr>
<tr>
<td>Pulmonary edema</td>
</tr>
<tr>
<td>Unstable angina</td>
</tr>
<tr>
<td>Acute myocarditis or pericarditis</td>
</tr>
<tr>
<td>Uncontrolled severe arterial hyperten-</td>
</tr>
<tr>
<td>Severe aortic stenosis</td>
</tr>
<tr>
<td>We added unstable asthma to this list</td>
</tr>
</tbody>
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*From ERS Task Force.*

Clinical Investigations
by McManus and Leung for congenital heart disease); (2) to reassure parents of a child with a chronic disease (such as cystic fibrosis or heart disease) by showing them that the child can carry out maximal exercise without problems or negative effects on the disease; and (3) to achieve VO_{2}max, a quantifiable index (to follow, with repetition of the tests, the functional handicap and progression of the chronic disease; to help in prognosis as shown by Nixon et al for cystic fibrosis; to measure and express the ventilatory threshold as a percent of VO_{2}max). A precondition of the determination of ventilatory threshold is the achievement of VO_{2}max. The HR measured at the ventilatory threshold level was used to initiate individualized readaptation in children with cystic fibrosis and in children with severe asthma who suffered dyspnea when running or practicing other endurance activities.

The rate of increase in work affects the value of VO_{2}max achieved, with protocols involving large increments resulting in lower values of VO_{2}max due to a lack of muscle power. Similarly, a low rate of increase in workload prolongs the duration of the test, making it a test of endurance, with lower values of VO_{2}max recorded. The duration of the test used herein made it possible to approach VO_{2}max in children. The optimal duration recommended, as stated by Buchfuhrer et al, is 10 ± 2 min, to make it possible for the maximum VO_{2}max to be achieved. This VO_{2}max is probably that which approaches most closely the original definition of VO_{2}max, enabling the body to make use of its reserves to increase its major vital functions to their maximum.

In the studied ill children, the VO_{2}max predicted at the start of exercise was achieved in 65.7% of the tests. The mean VO_{2}max recorded differed between the sexes, with a mean value of 32.2 ± 7.7 for girls and 41.3 ± 11.1 for boys. These values are lower than those for healthy children of the same age, with a “symptom-limited VO_{2}max” being reached, lower than the predicted value in many of these children. This limitation was essentially respiratory in nature.

This protocol favors maximization of VO_{2}max rather than power. The relationship between VO_{2} and power during exercise tests in healthy adults was determined by Hansen et al. This relationship was used in the individualized protocol (10.3 mL of O_{2}/kg/min). If a test is maximal, as shown by the VO_{2}max achieved, cardiac and respiratory adaptations, muscular aerobic oxidative potential, and muscular contractility come into play. Costill et al demonstrated in athletes the dissociation of muscular power, the role of the contractile capacity of muscle, and VO_{2}, which depends on muscular aerobic potential. Healthy children have a high VO_{2}max (mean value of about 50 mL/kg/min), but their muscular power is poorly developed. Thus, protocols in children should favor the maximization of VO_{2}max rather than workload.

The relationship between VO_{2} and power has been described in patients with respiratory diseases and in normal children. However, in these two populations, the Wmax obtained for a given VO_{2}max is usually lower than that calculated using the VO_{2}-power relationship because the ventilatory yield is low and much of the oxygen consumed is used by the muscles of the respiratory system. This relationship between VO_{2} and power, often deficient in children who are also ill, accounts for the changes in workload that we made in some cases during the final increments, if we estimated that the VO_{2} achieved was likely to be higher than that predicted for the power developed.

Analysis of the criteria for maximality included exhaustion of the subject, VO_{2} plateau, HRmax, and RERmax. The motivation of the child to reach exhaustion was in most cases evident (profuse sweating, inability to maintain the desired exercise intensity, dyspnea, unsteady gait). The explanation of the test before its performance was important. The child knew that the exercise to be supported would be maximal and we insisted on this in the last stages, which were particularly difficult. If exhaustion did not appear to us to be clinically clear, we kept the child at the same workload for a few extra seconds, or simply increased the workload again, but to a lesser extent than for the previous increments, to check that the variables monitored (ventilation and HR) and VO_{2} did not increase. Our experience led us to seek the exhaustion of the subject. This is particularly important in children, because even children with chronic diseases are more physically active than adults. The level of activity or physical training and the VO_{2}max measured are correlated in children and physical activity should lead to a higher VO_{2}max being reached in ill children than in ill adults. Clearly, the values obtained in an exercise test depend on the level of exercise, and it is extremely important to encourage ill children as strongly as healthy children to prevent bias in the interpretation of results. The subjective criteria for maximal exercise tests, including evaluation of the clinical exhaustion of the subject, depend, however, on the experience of the technician in the performance of these tests.

There are many criteria for the achievement of a VO_{2} plateau. The criterion used herein was an increase in VO_{2} of no more than 2 mL/kg/min for an increase in work of 5 to 10%. This criterion appeared to us to be the most suitable for our system of measurement and for an increase in workload every minute. A VO_{2} plateau was achieved in 68.4%
of all children (63 of 92 subjects), and in 58.7% of the prepubescent children (37 of 63, not significant). In published studies, only about a third of prepubescent children have been reported to achieve a \( \text{VO}_2 \) plateau; for others, a peak \( \text{VO}_2 \) is reported.\(^2,3,1,32\) The individualized protocol thus makes it possible to achieve a \( \text{VO}_2 \) plateau in a higher proportion of children (two of three subjects, in our experience) than with other protocols, regardless of the state of the child with respect to puberty.

The achievement or lack of achievement of a \( \text{VO}_2 \) plateau is extremely variable for an individual subject, depending on the averaging of respiratory exchanges and the increase in workload.\(^3,33\) Several elements probably contributed to the high frequency with which \( \text{VO}_2 \) plateaus were achieved in these exercise tests: (1) the choice of system for monitoring gaseous exchange, using a mixing chamber; (2) the large number of samples for measured \( \text{VO}_2 \)(\(^2,32\) herein, respiratory exchanges were averaged over a long interval [20 s], including several respiratory cycles); and (3) the discontinuous increase in workload that, unlike continuous increases in workload, favors the observation of a \( \text{VO}_2 \) plateau.\(^3,32,34\)

In ill children, is it of value to obtain \( \text{VO}_2 \) values over several seconds or cycles, as is now possible using apparatus for measuring gaseous exchange from cycle to cycle? Armstrong et al.\(^2\) and Rowland\(^35\) have demonstrated that in children, a peak \( \text{VO}_2 \) taken over several seconds is an index of maximal exercise, even in the absence of a plateau. This individualized protocol thus made it possible to achieve a \( \text{VO}_2 \) plateau in most of the children, whatever the \( \text{VO}_2 \)max achieved and the age of the child.

HRmax (except in children with failing chronotropic function, the number of which was small in this study) was achieved in almost all of our patients. The mean HRmax was >190 beats/min, and HRmax values of 205 to 215 beats/min were frequently recorded. HRmax determination is essential. It is therefore important to encourage children to perform “supermaximal” tests, which are without risk, except in rare cases of children presenting with ischemic complications or cardiac rhythm problems like those encountered in adults. According to Armstrong et al.\(^2\) the achievement of HRmax is one of the most reliable criteria in children; our results are consistent with this hypothesis, with a strong correlation between achievement of HRmax and of a \( \text{VO}_2 \) plateau.

Armstrong et al.\(^2\) also found that RERmax was a reliable criterion for maximal exercise. In adults, the criterion used is a RERmax >1.1, and this is usually the best criterion for maximal exercise. In our experiments, RERmax was one of the least useful criteria for the determination of maximal exercise because nothing during the test predicted whether the RERmax of the child would be 0.9 or 1.1. The mean RERmax recorded herein (1.06) is similar to that generally observed in children.\(^3,2,6\) We found no correlation between a RERmax >1 and achievement of a \( \text{VO}_2 \) plateau or a HRmax of 90% the predicted value.

### Conclusion

This study shows that for a population of 92 patients with various diseases, individualization of the protocol for exercise testing in children was possible and the clinical tolerance of exercise was high. The test was safe. Adapting the increase in workload to each child increased the probability of achieving maximal exercise. Two other advantages of this individualized approach were the favoring of \( \text{VO}_2 \) over power and the optimum duration of the test (10 to 12 min). We found that the two best criteria for confirming that exercise was maximal (especially if a \( \text{VO}_2 \) plateau was not reached) were clinical exhaustion and HRmax (except in children with cardiac disease). The achievement of a \( \text{VO}_2 \)max plateau is also a criterion often found in this type of protocol. The use of preestablished protocols does not appear to us to be desirable in children. This individualized methodology should make it possible to expand the use of cardiopulmonary exercise tests in pediatrics, both for diagnosis and treatment.\(^16\) The indications for such tests are diverse, and include assessment of dyspnea, discrimination of simple breathlessness in prepubescent children, poor physical conditioning, and true pathologic limitation, in which examinations at rest are insufficient. The follow-up of chronic diseases (e.g., cystic fibrosis, interstitial lung diseases) and the evaluation of treatment (e.g., efficacy of a long-acting bronchodilator to prevent exercise-induced bronchospasm) are also frequent indications in pediatric patients.

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