Prediction of maximal heart rate in children and adolescents

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ABSTRACT

Objective: To identify a method to predict the maximal heart rate (MHR) in children and adolescents, as available prediction equations developed for adults have a low accuracy in children. We hypothesized that MHR may be influenced by resting heart rate, anthropometric factors or fitness level.

Design: Cross-sectional study

Setting: Sports medicine center in primary care

Participants: Data from 627 treadmill maximal exercise tests performed by 433 pediatric athletes (age 13.7±2.1 years, 70% males) were analyzed.

Independent variables: Age, sex, sport type, stature, body mass, BMI, body fat, fitness level, resting and MHR were recorded.

Main outcome measures: To develop a prediction equation for MHR in youth, using stepwise multivariate linear regression and linear mixed model. To determine correlations between existing prediction equations and pediatric MHR.

Results: Observed MHR was 197±8.6 b·min^{-1}. Regression analysis revealed that resting heart rate, fitness, body mass and fat percent were predictors of MHR ($R^2=0.25, p<0.001$), while age was not. Resting heart rate explained 15.6% of MHR variance, body mass added 5.7%, fat percent added 2.4% and fitness added 1.2%.

Existing adult equations had low correlations with observed MHR in children and adolescents (r=-0.03-0.34).

Conclusions: A new equation to predict MHR in children and adolescents was developed, but was found to have low predictive ability, a finding similar to adult equations applied to children.

Clinical relevance: Considering the narrow range of MHR in youth, we propose using 197 b·min^{-1} as the mean MHR in children and adolescents, with 180 b·min^{-1} the minimal threshold value (-2 standard deviations).

Key words: athlete; exercise; heart rate; pulse; youth

INTRODUCTION

Exercise tests are widely used in the pediatric age group. There are several common indications for pediatric exercise testing, in both healthy children and in those with various health conditions. These include assessment of functional capacity, mainly of the cardiac and pulmonary systems, and an evaluation of signs or symptoms that are induced or worsened by exercise.[1]

During an electrocardiographic exercise test, gaseous exchange during exercise is not usually measured, in contrast to a cardiopulmonary exercise test. In order to evaluate whether the tested individual had obtained a maximal or even a near-maximal effort during the exercise test, several objective and subjective signs are used e.g., a subjective feeling that the tested individual has performed a maximal effort; physical signs of intense effort (facial flushing, sweating, unsteady gait or uncoordinated movements); and the achievement of the predicted maximal heart rate (MHR).[1,2] In the absence of gaseous exchange measurements, attainment of MHR is the only objective sign.

In a progressive exercise test, heart rate rises in an almost linear fashion, and reaches its maximal value at peak VO_2.[3] Therefore, MHR commonly serves as a surrogate marker of peak performance in the exercise test. Yet in order to assess whether maximal performance had indeed been obtained, the actual MHR achieved by an individual should be compared against a normal reference value. Numerous MHR prediction equations had been developed for adults in the last three decades. These were based on data from tens of thousands of participants and from a wide age range (20-70 years old), various ethnicities, and different fitness and activity levels.[4-6] The equation of Tanaka et al.,[4] based on a meta-analysis of 351 studies on 18,712 adult participants, has a high accuracy (r=-0.90). The rate of decline and the y intercepts were not significantly different between men, women, sedentary, active, or endurance-trained participants. In a prospective, laboratory-based part of that study in 514 healthy individuals, a similar equation was obtained, with standard deviations ranging from 7 to 11 b·min^{-1} in the entire age-range [4].

In contrast to adults, data regarding MHR prediction in the pediatric population is scarce and controversial. The predictive ability of the two most commonly-used adult MHR equations (220 - age [7] and 208 - 0.7*age [4]) had been examined in the pediatric population in two small studies recently, with limited sample sizes;[8,9] the data show that although the Tanaka equation [4] performed better, those adult equations do not adequately explain the observed MHR variance in children. Previous studies showed the MHR is age-independent in both children and teens, [3,10,11] while others suggested the MHR may be age-independent only until puberty.[2] One study found that MHR during a cycle exercise test was significantly lower in overweight as compared with normal-weight adolescents, despite a similar maximal oxygen consumption,[12] suggesting that body mass may affect MHR. Finally, the possibility that MHR in the pediatric age range may just have one constant, average value around 200 b·min^{-1}, had also been suggested.[1,13,14] Collectively, it appears that there is no well-defined prediction equation, or an accepted cutoff value, for MHR in children and adolescents.

The aims of the present study were to identify factors that contribute to MHR in the pediatric population; to develop a prediction equation for MHR using clinical and anthropometric data; and to compare the performance of relevant adult prediction equations in children and adolescents. We hypothesized that MHR in children would be age- and sex-independent, but may be influenced by resting heart rate, anthropometric factors or fitness level.

METHODS

Setting and participants

The data for this cross-sectional study were obtained from a sports medicine center in Israel, where amateur and competitive athletes of all ages routinely undergo pre-participation examinations, frequently including exercise testing. Computerized records in this center were used from 2007; all available data until November 2014 were collected. Data extracted from the records were age, sex, sport discipline, stature, body mass, body-mass index (BMI), body fat percent, maximal metabolic equivalents (METs) obtained, ergometer type, blood pressure and resting and maximal heart rate. Stature, body mass and BMI were transformed to age- and sex-specific percentiles according to the reference curves of the Centers for Disease Control and Prevention (CDC), using the modified LMS approach.[15]. We categorized the study population by estimated pubertal status, using 14 years for females and 16 years for males as post-pubertal threshold values [16].

Inclusion criteria were age under 18 years and performance of an exercise test on a motorized treadmill in order to obtain the highest MHR possible, as cycle ergometers might produce a lower MHR.[17,18] The study was approved by the Institutional Review Board of Sheba Medical Center, Tel Hashomer, Israel, and conducted according to the Declaration of Helsinki and its later amendments.

The primary outcome of this study was the predicted maximal heart rate. Predictors used were age, sex, stature, body mass, BMI, body fat percent, fitness, and resting heart rate.

Anthropometric variables

Stature was measured using a wall-mounted stadiometer (Seca 206, Seca gmbh, Hamburg, Germany), to the nearest 0.1 cm. Body mass was measured using an electronic scale (Seca 700M, Seca gmbh, Hamburg, Germany) to the nearest 0.1 kg and BMI was calculated. Body fat percent was calculated from the sum of two skinfolds (triceps, measured vertically on the back of the right arm, midway between the top of the acromion process and the olecranon process, and calf, measured in the right lower leg at the greatest calf girth), measured using a Skyndex Electronic Skinfold Caliper (Caldwell, Justiss & Co., Inc., Fayetteville, AR, USA), and using the built-in Slaughter-Lohman formula.[19]. We calculated the amount of fat free mass from body fat percent and body mass, and calculated the fat free mass index (fat free mass in kg divided by stature squared, kg/m^2).

Exercise testing protocols

All participants routinely underwent inspiratory and expiratory spirometry prior to exercise testing by a computerized analyzer (ZAN ErgoSpiro 680, nSpire Health, Inc. Longmont, CO, USA). Participants with evidence of restrictive or obstructive flow-volume loops were excluded from analyses (n=11).

Participants performed a graded exercise test on a treadmill (Run MED, Technogym SpA, Cesena, Italy) using one of several protocols, according to the participant's age and anticipated fitness level. In general, the maximal speed was 10-11 km·h^{-1} for males and 8-10 km·h^{-1} for females, after which inclination of the treadmill would rise at a rate of 1% per minute until volitional fatigue. The exercise tests were symptom limited, and terminated when the participant asked to stop, while reporting maximal ability and showing clinical signs of intense effort. A standard 12-

lead electrocardiogram was used to analyze cardiac rhythm in the supine position at rest and throughout the exercise test. At the end of the test, electrocardiogram tracings at peak exercise were reviewed by the exercise technician and MHR was manually measured, in order to verify the automatic calculation provided by the system. In case of discrepancy, the manual measurement was used. Maximal METs were automatically calculated by the system using the maximal grade and inclination achieved by the tested individual.

Statistical analysis

Continuous variables were described using mean and standard deviation. Categorical variables were described as frequency and percentage. In participants that performed several exercise tests (e.g., on an annual basis), the primary analyses included only data from the first test performed, in order to avoid over-sampling of these recurring children. The relationships between MHR and continuous variables were evaluated using Pearson's correlation coefficient.

MHR was compared between males and females using unpaired t-tests. Multivariate linear regression using the stepwise method was used to identify predictors for max HR, after verifying the regression assumptions (multi-collinearity, homoscedasticity, and normal distribution of the residuals). The regression and other available adult prediction equations were evaluated using scatterplots and Pearson's correlation. Analyses such as concordance correlation coefficient or intraclass correlation coefficient were not used, because of low Pearson's correlation coefficients found.

Interactions that were found in previous prediction equations or were assumed as relevant in our sample were also evaluated (e.g. age X sex, age X resting heart rate). Finally, a linear mixed model was used to evaluate the association between MHR and the predictors identified by the linear regression, while also including data from the whole sample (i.e., including repeated exercise tests performed by same individuals annually). Root mean squared error (RMSE) was used to evaluate the goodness-of-fit of the model.

IBM SPSS Statistics software version 21 was used for data analysis. A two-tailed p value of <0.05 was considered as statistical significance.

RESULTS

The database included 627 maximal exercise tests. Examination of identification numbers disclosed that the exercise tests were performed by 433 different participants, of which 305 were males (70.4%). Demographic and anthropometric measures of the 433 study participants are presented in Table 1. Twenty-five percent of the tests were performed by post-pubertal participants. Participants trained in 27 different sport types, most frequently being middle-school competitive sports class (n=95, 21%), basketball (n=76, 17%), swimming (n=65, 14%), tennis (n=50, 11%) and triathlon (n=34, 8%). Other sport disciplines included various types of martial arts, gymnastics, soccer, handball, water polo, equestrian, sailing and surfing. No participant had abnormal blood pressure or electrocardiogram tracing at rest, during exercise or during recovery.

The measured mean MHR was 197±8.6 b·min^{-1}, range 170-218 b·min^{-1}. A MHR of 180 b·min^{-1} was obtained by 97.2% of the participants, both when examining first-test only conditions (n=433) and the whole dataset of exercise tests (n=627). There was a small but significant mean sex difference of 2.5 b·min^{-1} (males 196.0±8.9 b·min^{-1}, females 198.5±7.7 b·min^{-1}, p=0.005). Table 2 presents Pearson's correlation coefficients between MHR and the various continuous variables. In general, despite statistical significance in most cases, no single variable had a strong correlation with MHR and could only be described as weak correlates.

MHR prediction equation

Multivariate linear regression revealed that only resting heart rate, fitness level, body mass and fat percent were identified as predictors of MHR. Resting heart rate explained 15.6% of the variance in MHR, body mass added 5.7%, fat percent added 2.4%, and fitness level added 1.2%.

The prediction equation obtained was:

(1) MHR= 168 + 0.259 X resting HR – 0.156 X body mass (kg) + 0.891 X METs + 0.256 X body fat percent

(R^2=0.250, $p<0.001$, standard error of the estimate (SEE) 7.54).

The error range of prediction equation number (1) ranged from -25 to +20 b·min^{-1}, which are -13% to +10% from the mean observed MHR. The difference between the measured and predicted MHR using this equation had a standard deviation of 7.5 b·min^{-1}. Figure 1 shows the relationship between observed MHR and predicted MHR using equation number (1). It was found that the equation overestimates MHR in the lower values, and underestimates MHR in higher values.

Since MET level and body fat percent are not always readily available, and may vary by measurement methods, a more simplified prediction equation without these two parameters was also developed:

(2) MHR=186 + 0.25 X resting HR – 0.14 X body mass

(R^2=0.214, $p<0.001$, SEE 7.69)

The error range of this prediction equation number (2) ranged from -24 to +17 $b \cdot min^{-1}$, which are -14% to +8%.

The equations obtained from the linear mixed models, which also included data from 113 participants that performed several exercise tests, were very similar:

(1a) MHR= 164 + 0.270 X resting HR – 0.155 X body mass (in kg) + 1.1 X METs + 0.258 X body fat percent

(RMSE = 7.35)

(2a) MHR=186 + 0.25 X resting HR – 0.13 X body mass

(RMSE = 7.55)

Interactions between age and sex or age and resting HR were not associated with MHR (p=0.56 and p=0.77, respectively).

Comparing observed MHR with adult prediction equations

Table 3 presents Pearson's correlation coefficients between the MHR and several existing adult MHR prediction equations. Using scatterplots (Figure 2), we observed that at higher observed MHR values, all prediction equations underestimated MHR in our sample; at lower heart rates, the prediction equations overestimated MHR.

DISCUSSION

The aim of this study was to identify a method to predict MHR in children and adolescents. After examining several clinical and anthropometric variables, very few were found to be significantly associated with the observed MHR, and with only weak associations. The small between-sex difference seen of 2.5 b·min^{-1}, though statistically significant, has little clinical relevance and is much smaller than the variation observed in the whole cohort.

Our findings are in general agreement with previous large studies in adults, which showed that MHR was independent of sex, race, physical activity, fitness level, or BMI.[4,18,24] The single factor that was repeatedly found to affect MHR in adults is age, as shown in Table 3. We, as well as others,[3,8,9,10,11] did not find that age, estimated post-puberty status or age-based equations had a high predictive ability for MHR in the pediatric age range (Figure 2 and Table 3). Interactions between age and sex or age and resting HR were also not associated with MHR. There are two main possible explanations to this lack of age-dependency of MHR in children, as opposed to the significant relationship between age and MHR in adults. Firstly, the relevant age range in studies of pediatric exercise testing is narrower than in adults, spanning only 10 years, from about 8 to 18 years. Adult studies have a much large age span, of 60 [4,26] and even 70 years.[24] Shargal et al.,[26] in a study of over 28,000 participants, showed that while MHR does decline significantly across a wide age range, it does so much less when the study population was divided by 10-year intervals. A second possible explanation is that in adults, MHR may decline from early adulthood to older age, as part of overall senescence seen in many body systems, as well as in aerobic fitness.[27] In marked contrast, youth is a time of growth, development and maturation, with constant and rapid changes in body size, body composition, physical fitness and athletic performance. Despite such significant changes that occur during youth, aerobic fitness relative to body size remains fairly constant in the pediatric age range in boys.[11] MHR may behave similarly in this period.

The new MHR prediction equation developed for children and adolescents in this study, based on a large dataset utilizing treadmill tests only, had a low correlation with MHR, even after taking into consideration several clinical and anthropometric factors. The single factor found to have the highest relationship with MHR was resting heart rate. Of the several adult prediction equations examined, the one that had the highest correlation coefficient was that developed by Mahon et al.,[9] which includes the resting heart rate. The addition of resting heart rate to the MHR prediction equation coincides with exercise intensity prescription in adults, which is currently best described as percent of the heart rate reserve (i.e., the difference between resting and maximal heart rate), rather than as percent of maximal heart rate alone.[28] The percent of heart rate reserve accurately reflects the same percentage as the VO_2 reserve, and thus parallels the intensity of cardiorespiratory exercise.[28]

Collectively, our findings show that at present, there is no reliable prediction equation for MHR in children and adolescents. Considering the narrow range of MHR in youth, its independence from age, sex and body size, and the lack of accurate prediction equations in both our study and others, we propose using 197 $b \cdot min^{-1}$ as the mean MHR in children and adolescents, with 180 $b \cdot min^{-1}$ being the minimal threshold value (-2 standard deviations, which represent the commonly-accepted lower limit of normal values). The mean MHR found in our sample, and its standard deviation, are nearly identical to that found in a large sample of 6,557 participants aged 10-19.9 years that performed a maximal treadmill test (196 ± 7.6 b·min^{-1}).[26] Further, attaining a heart rate of 195 b·min^{-1} was previously found to be the most robust secondary criterion to verify achieving VO_2 max in children.[29] The suggested minimal threshold of 180 b·min^{-1} was obtained by 97.2% of the participants, both when examining first-test only conditions (n=433) and when examining the whole dataset of 627 exercise tests. This approach, of using mean and standard deviations as a normal range, thereby using a single cutoff value to define a normal limit, is used in numerous other laboratory tests in medicine. In fact, there are very few variables where prediction equations are used in research or clinical settings instead of fixed threshold values.

As with all studies, several limitations should be acknowledged. Our sample size, although significantly larger than previous pediatric studies that developed or examined MHR prediction equations, was still limited. For comparison, the Tanaka prediction equation for MHR in adults was developed using data from 351 studies on 18,712 participants.[4] Second, we used data from an existing database obtained from clinical measurements, and did not perform a designated laboratory-based study. However, this setting truly reflects real-life conditions, of children coming to perform a maximal treadmill exercise test for clinical reasons, and therefore our findings can be directly translated to the clinical setting. It should be noted that in the study by Tanaka et al.,[4] the regression equation obtained from their laboratory-based study was virtually identical to that obtained from the meta-analysis of clinical samples. Finally, as the study population consisted of relatively active children and adolescents mostly of normal weight, its generalizability to sedentary or overweight children might be limited. However, in their large study in adults, Tanaka et al. [4] reported that there were no significant differences in MHR between sedentary, active or endurance-trained participants. In our sample, we also found that MHR did not correlate with METs in the univariate analysis. In the linear regression, METs explained only 1.2% of the variance in MHR, which is only about 2 $b\cdot min^{-1}$. Nevertheless, active children are usually the ones who undergo such maximal exercise testing and need heart rate-related exercise prescriptions. Our results, which were obtained from this exact population, can therefore be used with greater confidence in active children and adolescents than in sedentary ones.

The main strengths of our study were: 1) the relatively large number of participants, compared with previous pediatric-only studies; 2) the use of several clinical and anthropometric factors as possible predictors for MHR, for the first time in children and adolescents (age, sex, stature, body mass, BMI (and their age- and sex-specific percentiles), body fat percent, fitness level, and resting heart rate); 3) the two approaches of analyses using both the first-test only from each participant, and a mixed-model which included repeated tests by same individuals; 4) the inclusion of participants from a wide range of athletic activities and fitness levels; and 5) the use of data only from treadmill tests, which commonly produce a higher MHR than cycle ergometers.[17,18]

In summary, in this study of 627 maximal exercise tests performed by 433 children and adolescents, very few clinical and anthropometric variables were found to be significantly associated with MHR, and by a very small magnitude. A new prediction equation for MHR in the pediatric age range was developed, yet which had a low predictive ability, as did several relevant adult equations examined. Adding that numerous clinical and laboratory values in research and clinical practice do not have prediction equations but single cut-off values, we suggest using 197 b·min^{-1} as the mean MHR in children and adolescents, with 180 b·min^{-1} the minimal threshold value for exercise treadmill testing.

CONFLICTS OF INTEREST AND SOURCE OF FUNDING

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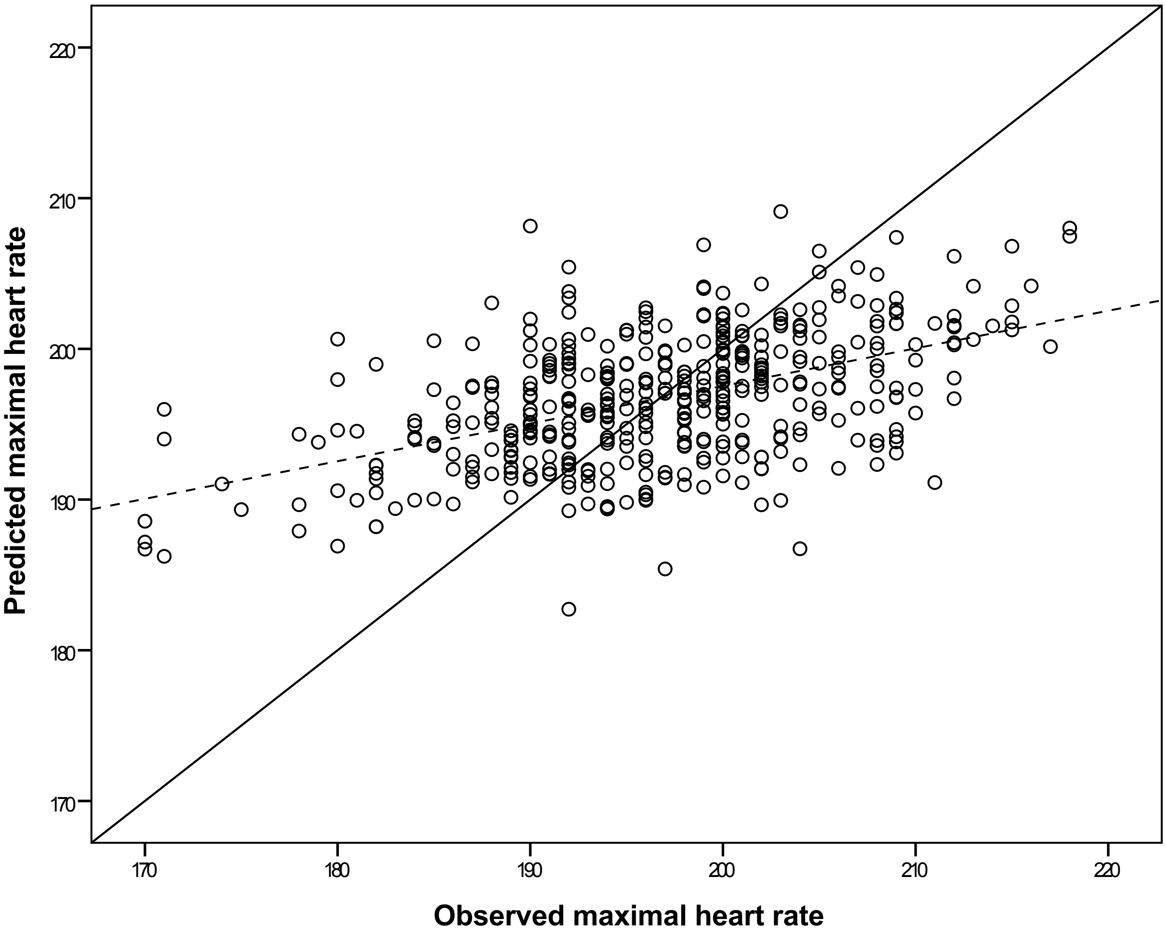
FIGURE LEGENDS

Figure 1: The relationship between observed MHR and predicted MHR obtained using the new prediction equation. The dashed line is the regression line (R^2=0.250, $p<0.001$). The diagonal 45º line represents a perfect potential agreement between observed and expected values.

Figure 2: The relationship between observed MHR and predicted MHR obtained using several adult prediction equations.


Predicted maximal heart rate
220
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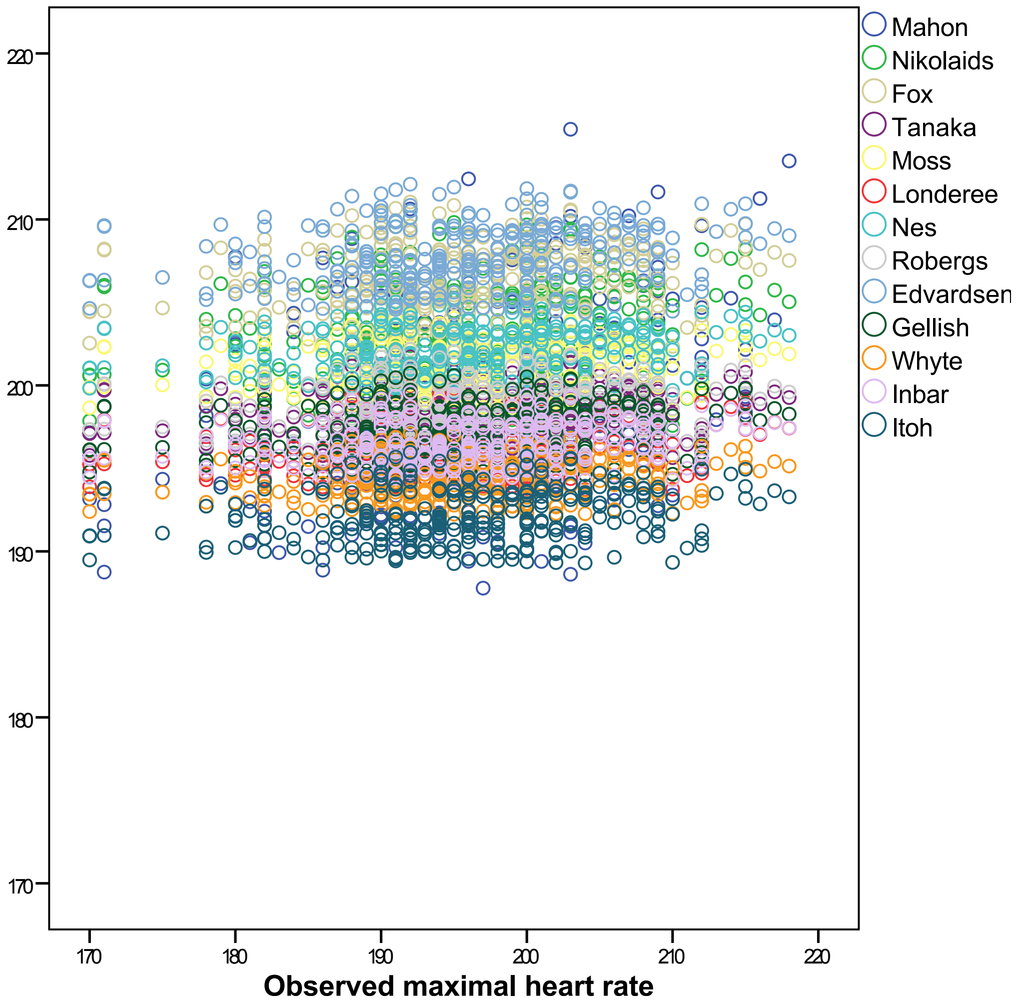
Observed maximal heart rate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Observed maximal heart rate
Mahon
Nikolaids
Fox
Tanaka
Moss
Londeree
Nes
Robergs
Edvardsen
Gellish
Whyte
Inbar
Itoh

Table 1: Demographic and clinical characteristics of the study participants at first visit (n=433).

	Mean (SD)	**Range**
Age (years)	13.7 (2.1)	9.0-17.8
Body mass (kg)	53.5 (15.4)	25.0-112.0
Body mass (percentiles)	59.0 (27.8)	0.0-99.6
Stature (cm)	162.1 (13.5)	134.0-204.0
Stature (percentiles)	60.6 (28.4)	0.2-99.9
BMI (kg/m^2)	19.9 (3.4)	12.9-32.3
BMI (percentiles)	54.3 (27.6)	0.1-98.6
Body fat percent (%)	17.2 (6.4)	6.4-40.0
Fat-free mass index (kg/m^2)	16.6 (2.5)	10.5-26.0
METs	15.4 (2.1)	10.0-22.9

Table 2: Pearson's correlation coefficients between observed maximal heart rate and the continuous variables.

	Correlation coefficient	p value
Age (years)	-.278	<0.001
Stature (cm)	-.321	<0.001
Body mass (kg)	-.307	<0.001
BMI (kg/m^2)	-.190	<0.001
Stature (percentiles)	-.137	.004
Body mass (percentiles)	-.172	<0.001
BMI (percentiles)	-.107	.026
Body fat percent	.156	.001
Fat-free mass index	-.280	.026
Resting HR (b·min^{-1})	.395	<0.001
METs	-.045	.355

Table 3: Pearson's correlation coefficients between measured MHR and listed MHR prediction equations.

Source, year	**Equation**	**Correlation coefficient**	**p value**
Fox, 1971 [7]	220-Age	0.278	<0.001
Londeree, 1982 [18]	206.3-0.711*Age	0.278	<0.001
Inbar, 1994 [20]	M: 205-0.605*Age	0.207	<0.001
Moss, 2000 [13]	210-0.65*Age	0.278	<0.001
Tanaka, 2001 [4]	208-0.7*Age	0.278	<0.001
Robergs, 2002 [5]	208.754-0.734*Age	0.278	<0.001
Gellish, 2007 [21]	207-0.7*Age	0.278	<0.001
Whyte, 2008 [22]	M Athletes: 202-0.55*Age F Athletes: 216-1.09*Age	0.234	<0.001
Mahon, 2010 [9]	158.4+0.44*Rest HR+0.68*Age	0.335	<0.001
Edvardsen, 2013 [23]	M: 220-0.88*Age F: 208-0.66*Age	-0.023	0.63
Itoh, 2013 [16]	202.8-0.763*Age-11.1*Sex+0.209*(Sex*Age)	-0.030	0.53
Nes, 2013 [24]	211-0.64*Age	0.278	<0.001
Nikolaidis, 2015 [25]	223-1.44*Age	0.278	<0.001