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Research Article

Disparity between estimates and measures of maximum heart rate in pilots with coronary artery disease

Abstract

Background : Several studies indicate that HRmax estimates using the traditional equation, *HRmax = 220 - Age*, may represent a regression slope and intercept that does reflect the true relationship between age and maximal cardiac frequency. Meta-analysis of several pertinent studies indicates that *220-Age* significantly under-estimates the true HRmax, particularly in older patients. This is a critical issue in the exercise evaluation of pilots with CAD who seek reinstatement of an aviation medical certificate after a cardiac illness because end-points in exercise testing and fitness assessment are based upon the 220--Age method of HRmax estimation.

Objective: This study was conducted to assess the accuracy of HRmax estimates made with the traditional method, 220-Age, in pilots with coronary artery disease

Methods: Nineteen male pilots, aged 46 to 82 years, with a history of CABG or multi-vessel PCI, exercised to exhaustion on a Bruce treadmill protocol. HRmax was measured from continuous 12-lead ECG and regressed on age by linear methods. The resulting regression equation was compared to other equations, including *220-Age*.

Results: Measured HRmax was highly correlated with age (r = -0.95) and represented by the regression equation, *HRmax = 226 – Age*. HRmax estimates generated by the 220-Age method were significantly less (p<0.001) than measured HRmax.

Conclusions: The traditional method for predicting HRmax under-estimates the maximal cardiac frequency in male pilots with CAD. The accuracy of HRmax estimation for pilots with CAD was not improved by using regression equations derived by meta-analysis of several hundred studies.

Introduction

The heart rate maximum (HRmax) achieved in exhausting exercise is an important variable in the practice of aviation medicine, in both civilian and military sectors. Aside from its widespread use in performance studies to identify maximal aerobic capacity of aviators (1), HRmax is used to develop exercise prescriptions for fitness maintenance [2,3], and to assess the fitness of flight crew (1,3,4). HRmax is also used to derive end-points in diagnostic exercise testing of pilots suspected of having ischemic heart disease or dysrhythmia [5,6]. After a cardiac illness, such as myocardial infarction, coronary artery by-pass graft surgery, valve replacement or repair, or percutaneous stent deployment in a coronary artery, HRmax may be used to regulate rehabilitation exercise intensities and develop guidelines for pilots who should maintain an independent exercise program [6,7]. Furthermore, HRmax has been identified as the critical target HR that must be achieved in the assessment of a pilot's exercise capacity, health status, and fitness for resumption of flying [8,9].

Prior to an exercise test, the target HRmax (bpm) is traditionally estimated by subtracting the subject's age from 220. The convenience of this simple calculation contributed to its widespread acceptance over the past 50 years and fostered the assumption that it yields accurate estimates of the true HRmax over a wide range of ages and fitness levels [10-14]. In critical reviews of the concept, Robergs and Landwehr [14] and Tanaka et al. [15], offered a contrary opinion. In a meta-analysis that included 18,712 subjects, Tanaka et al. [15], found that the equation HRmax = 220 - Age significantly under-estimated the highest attainable HR for persons aged 40 years or more. In a prospective study of 514 subjects, they found better regression equations appropriate for healthy, sedentary, active, and

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trained subjects. Subjects with a history of coronary artery disease (CAD) or ECG evidence of ischemia were not included in their study, however. Tanaka et al. [15], also demonstrated that under-estimations of HRmax using 220 - Age could result in erroneous measures of aerobic fitness and inaccurate exercise prescriptions. An extensive review of 43 pertinent HRmax studies by Robergs and Landwehr [14], supports that finding. Furthermore, Tanaka et al. [15], and Robergs and Landwehr [14], pointed out that use of the 220 - Age equation could cause diagnostic exercise tests to be terminated prematurely due to under-estimation of the true HRmax, particularly in older subjects.

This is an important issue in the evaluation of pilots after a cardiac illness because the Federal Aviation Administration [8] specifies that pilots must achieve 100% of the HRmax in an exercise test before an aviation medical certificate can be reinstated. Implicit in the FAA requirement is the assumption that the 220 - Age predicted HRmax is an accurate approximation of the true physiologic maxima for cardiac frequency and that it provides a thorough evaluation of the heart at its true limit of performance. If the traditional method of calculating target HRmax results in a heart rate that is significantly less than the true physiologic maxima, however, the assessment of a pilot's fitness capacity may be erroneous and incomplete.

The present study was undertaken to assess the accuracy of HRmax estimates produced by the equation, HRmax = 220 – Age, in civilian pilots who sought reinstatement of an aviation medical certificate after a cardiac illness resulting from coronary artery disease. It was hypothesized that 220 – Age would consistently under-estimate the HRmax measured during exhausting treadmill exercise. A complementary objective was to compare the HRmax/Age regression equation derived for pilots in the current study with equations derived for healthy sedentary and active subjects reported by others [15-19].

Methods

Twenty male civilian pilots gave their informed consent to participate in this study. One subject was excluded due to rapid atrial fibrillation during the exercise test. No female pilots with coronary artery disease were referred for testing during the period of this study. Anthropometric characteristics of nineteen subjects are given in table 1.

All of the pilots had been previously diagnosed with coronary artery disease (CAD) Eight subjects (42%) underwent coronary artery bypass graft surgery (CABG). The remaining 11 (58%) subjects were treated with percutaneous coronary angioplasty with endovascular stent placement in two or more arteries. Two pilots had mitral valve repair with single-vessel CABG surgery.

Table 1: Characteristics of 19 pilots with coronary artery disease.

	Age (years)	Weight (kg)	Height (cm)	BMI
Mean	61.4	86.3	179.6	26.7
1 SD	10.1	13.7	6.5	2.7
Range	46-82	65.9-106.8	166.4-190.5	23.1-30.9

Exercise tests were conducted a minimum of six months from the date of surgery, PCI, or most recent hospitalization for a cardiac illness. Prior to testing all subjects were evaluated by a cardiologist or specialist in internal medicine. Beta-blockers and non-dihydropyridine calcium channel blockers were withheld during the 48 hours prior to testing.

All subjects voluntarily presented for testing in order to obtain a special issuance medical certificate from the FAA. Most of these subjects (65%) participated in our cardiac rehabilitation program specially designed for pilots described previously [6]. All subjects were physically active and engaged in regular, independent aerobic exercise according to a traditional exercise prescription [10]. Two subjects sought a Class I medical certificate required for operation of large commercial jet aircraft. Thirteen subjects sought a Class III certificate for recreational or business flight in small aircraft. The remaining subjects required a Class II certificate for work as flight instructors.

Per FAA specifications, all subjects performed incremental exercise following a Bruce treadmill protocol. Prior to exercise, the 12-lead ECG was recorded, with blood pressure, in sitting, standing, and during a brief period of hyperventilation. Throughout exercise and the recovery period, blood pressure was recorded each minute while HR, 12-lead ECG, and rhythm were monitored continuously. All test were conducted according to the standards and guidelines of the American College of Cardiology and American Heart Association [11]. Ten subjects were available to perform a second exercise test which afforded an opportunity to assess the statistical reliability of HRmax measurements.

The HRmax was calculated from the average R-R interval during a 6-second ECG recording made when the subject indicated he was exhausted and unable to continue exercise. Prior to exercise, the age-predicted HRmax was calculated with the equation, *HRmax = 220 - Age*, using age, in years, rounded to the nearest whole number. An additional estimate of HRmax was made for each subjects using the equation of Tanaka et al. [15], HRmax = 208 – 0.7Age.

Subjects were motivated by prior FAA notification that special issuance of an aviation medical certificate would not be granted unless they completed a minimum of nine minutes of exercise (10.0 METs) in accordance with the Bruce treadmill protocol and achieved a peak HR equal to the age-predicted HRmax, using HRmax = 220 - Age. They were informed by the investigator that exercise would continue beyond those end-points if there was no medical indication to terminate the test [11].

Furthermore, subjects were advised that they had the option of stopping the test at any time for any reason. They were specifically advised to stop exercise if they experienced; 1). Chest symptoms consistent with angina, 2). Dyspnea or other ventilatory discomfort that indicated to them that an exercise limit had been reached, 3). Localized lower-extremity muscle or joint pain, 4). Discomfort such as nausea, back pain, dizziness, lightheadedness, 5). Visual disturbances, or

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6), Sensations of near-syncope. If none of these indications of exercise intolerance occurred, subjects were advised to stop when they felt they had reached their maximal exercise capacity due to; 1). General lower-extremity muscle fatigue, 2). Fatigue of the muscles of ventilation, or 3). A distinct impression that all energy had been expended.

Statistics

Descriptive statistics (mean and SD) were computed with Microsoft Excel for HRmax measured in exercise and estimated by the regression equations HRmax = 220 - Age and HRmax = 208 – 0.7Age, and additional equations reported by others [14-16,18]. Differences between the measured and estimated HRmax were assessed with repeated-measures single-factor ANOVA. The Newman-Keuls statistic was used for post hoc analysis of differences between two means of paired samples. The level of significance was set, a priori, at 0.025 for all analyses.

Linear regression analysis with calculation of the Pearson product-moment correlation, r, was performed to describe the association between age and measured HRmax. Bland-Altman plots were generated to display individual differences in measured and estimated HRmax. Slopes of various linear regressions between age and measured or estimated HRmax were compared with the method of Zar [20]. This statistic generated a P value that tests the null hypothesis that regression slopes are identical. The reliability of measured HRmax was assessed in 10 subjects with Student's t-statistic and Pearson correlation coefficient applied to repeated measures.

Results

All subjects completed the exercise test without symptoms or ECG indications of myocardial ischemia. Furthermore, none of them displayed abnormal blood pressures, dysrhythmia, or significant ectopy. In every case, exercise was terminated by the subject due to general fatigue. Each subject achieved a Borg scale rating of 19-20 associated with the impression of "very, very hard" work. Test-retest assessment of HRmax measures for ten subjects yielded a correlation coefficient, r, of 0.97 and a t-ratio of 0.54 ($p<0.02$).

The regression of measured HRmax on age yielded an r of -0.95 (Figure 1). The regression slope for those data was identical to that of the traditional HRmax prediction equation but the intercept was greater. A Bland-Altman plot (Figure 2) depicts individual differences between measured HRmax and estimated HRmax using 220 - Age. Disparity between the two methods averaged 6.6 beat per minutes and was not age-related.

A repeated measures ANOVA indicated highly significant ($p<0.001$) differences between estimates of HRmax using 220 - Age, measured HRmax obtained in the present study, and HRmax estimates for the subjects made with the equation of Tanaka et al. [15], 208 - 0.7Age. Post hoc analysis revealed that the measured HRmax were significantly greater than estimates based on the traditional method, 220 - Age (Table 2).

Similar results were found when HRmax estimates generated by Tanaka's equation were compared to estimates derived with the traditional equation.

Regression slopes for measured HRmax and HRmax estimated with the equation of Tanaka et al. [15], derived from more than 18,000 subjects, are compared in figure 3. A Bland-Altman plot (Figure 4) indicates a tendency for Tanaka's equation to over-estimate the HRmax of older pilots with CAD. The measured HRmax of the four oldest subjects was 5-8 bpm less than values estimated with Tanaka's equation. A simple t-test for paired measures, however, indicated no significant difference between measured and estimated HRmax over an age range of nearly 40 years.

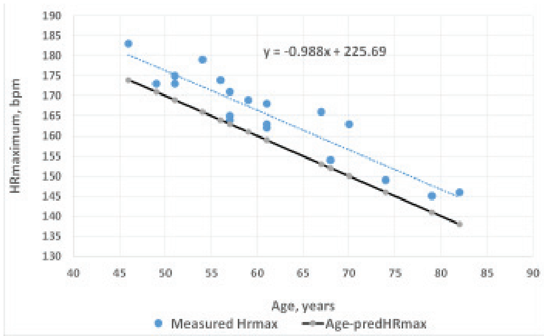

Figure 1: Refression of measured and estimated (HRmax (220-Age) on age (N=19).

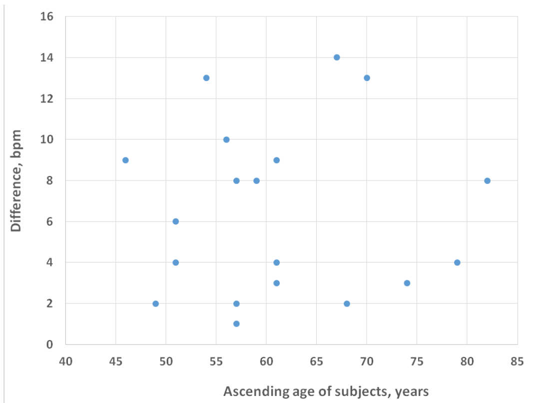

Figure 2: Bland-Altman plot of individual differences in measured versus estimated (220-Age) HRmaximum (N=19). Mean = 7.0.

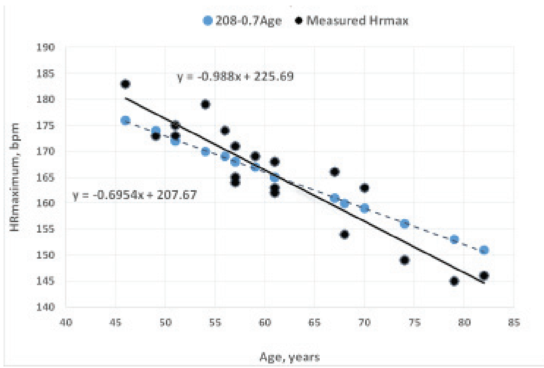

Figure 3: Regression of measured HRmax and estimated HRmax (208-0.7Age) on age (N=19).

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After achieving the age-predicted HRmax, subjects continued exercise on the treadmill nearly one minute longer as HR increased to the highest measured value (Table 3). The additional exercise time involved a change in speed and grade for 42% of the subjects, giving them a higher MET estimate.

Zar's statistic [20] for comparison of regression slopes and Newman-Keuls t-statistics were applied to the measured HRmax and HRmax estimates obtained from equations reported by other investigators (Table 4). In every case, measured HRmax of pilots with CAD differed significantly from estimates generated by equations derived from healthy sedentary subjects [18], healthy active subjects [18], fitness program participants [17], endurance athletes [21], obese males [22], patients with heart disease [23], and hypertensive males [19].

Discussion

The traditional equation for estimation of HRmax developed by Fox and associates [24,25]. in the 1970s failed to accurately predict HRmax in pilots with coronary disease. In every case, measured HRmax exceeded predictions made with *HRmax = 220 - Age* with a mean difference of 6.6 +/- 4.3 beats. Several subjects exceeded the predicted value by 10 beats or more. Tanaka et al. [15], made a similar comparison in 514 healthy subjects but they did not report the mean of individual differences. They did report that in subjects aged 70 to 80 years, measured HRmax were 12-18 beats greater than the predicted values. Whaley et al. [16], reported a mean of individual differences of 19.8 +/- 4.4 beat in 166 healthy males aged 46 +/-10.1 years. Their discriminate analysis indicated that the discrepancy between measured and estimated HRmax was greatest in older, lighter weight, non-smoking subjects with low resting HR.

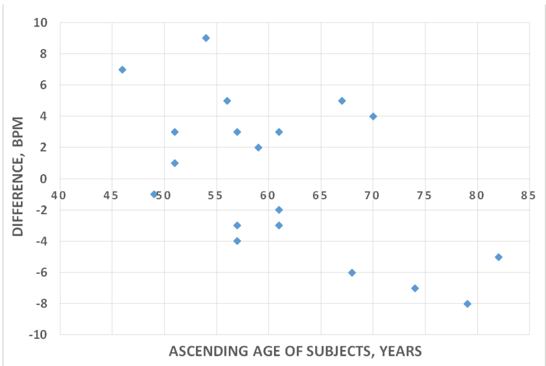

Figure 4: Bland-altman plot of individual diffrences between measured HRmax and estimated HRmax (208-0.7age). Mean = 3.1 BPM.

Table 2: Mean and one SD for measured HRmax and two estimates of HRmax with the means of individual differences between assessment methods (N=19).

	Measured HRmax	HRmax=220-Age	HRmax= 208-0.7Age
Mean	166.3	159.6	165.2
1 SD	10.2	9.8	7.5
Mean differences		6.6	5.9
1 SD		4.3	2.6
P		< 0.01	< 0.01

Table 3: Treadmill performance time (N=19)

	Time (sec) to HRmax	Time (sec) to Measured HRmax	Individual Difference Treadmill Time (sec)	Number Advancing
Mean	589.0	645.7	56.7#	8
1 SD	19.6	30.7	6.8	
Range	346-842	407-963		

* Number of subjects who continued exercise into the next stage after achieving age - predicted HRmax.
# *p* < 0.01

Table 4: Regression equations for estimating HRmax (bpm) from age (years) compared to an equation generated by pilots with CAD.

Source	Specification	Equation	r
Present study	Pilots with CAD	HRmax = 226 – Age	0.95
Wilson and Tanaka	18) Active M + F	HRmax = 206 – 0.7 Age	0.88
Wilson and Tanaka (18)	Trained M + F	HRmax = 205 – 0.6 Age	0.89
Lopez et al. (17)	Healthy males	HRmax = 204 – 0.8 Age	0.61
Lester et al. (21)	Trained M + F	HRmax = 205 – 0.41 Age	
Miller et al. (22)	Obese males	HRmax = 198 – 0.44 Age	0.39
Bruce (19)	Healthy males	HRmax = 210 – 0.66 Age	0.44
Bruce (19)	Hypertensive males	HRmax = 204 – Age	0.49
Hammond (23)	Males with CAD	HRmax = 209 – Age	
Graettinger (26)	Healthy males	HRmax = 199 – 0.63 Age	0.47

The inaccuracy of HRmax predictions made with 220 - Age was anticipated based on recent laboratory studies [15-17], summations of older studies [14,16], and the standard error of estimate (SEE) of 15 beats associated with this regression equation [10,23]. Most equations for estimating HRmax have a 95% confidence interval (CI) of +/- 40-60 bpm [13,17], making age-based predictions tenuous and limiting clinical utility. In contrast, the subjects of the present study generated a CI of +/-24 bpm with the equation *HRmax = 226 - Age*. Whaley et al. [16], found no significant improvement of CI with the addition of other independent variables to the regression equation such as body weight, resting HR, or smoking code. Graettinger et al. [26], reported similar results in hypertensive patients with the addition of indices of relative LV wall thickness and change in serum epinephrine / norepinephrine in exercise.

In the present study, the regression slopes for the traditional prediction equation and the equation for measured HRmax / Age were found to be identical. Based on the meta-analysis by Tanaka et al. [15], involving 351 studies with 18,721 healthy subjects, it was anticipated that the regression slope for pilots with CAD would approximate 0.7 because of the broad age range of their sample and high correlation coefficient between age and measured HRmax. The regression slope of 1.0, however, suggests that pilots for CAD may have a greater rate of decline of HRmax as age progresses compared to healthy subjects. Among healthy subjects, the regression slope was not affected by habitual exercise status, ranging from a sedentary lifestyle to rigorous endurance training, or gender [15,16].

The difference in intercept found in the current study, compared to value reported by Fox et al. [25], displayed in (Table 4), may be the result of the central characteristics of their

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database. In developing the equation HRmax = 220 - Age, Fox and associates [24,25], excluded subjects older than 65 years and included few subjects aged 55 to 65 years. Their database, comprised of ten studies, reportedly included subjects who smoked habitually with vaguely defined history of CAD, and others treated with beta-blocking medications. These factors have been found to influence that HRmax independent of age [15-17,26]. In addition, Fox et al. [25] may have included a preponderance of sedentary subjects unaccustomed to rigorous exercise. The pilots who served in the present study were tested at least 48 hours after withdrawal from HR-attenuating medications. All of them were physically active and followed a traditional exercise prescription for aerobic fitness [6,10]. Forty-two percent of subjects had more than 100 hours of experience in treadmill exercise as a result of participation in a cardiac rehabilitation program designed for pilots. None of the subjects had smoked within the preceding five years. Motivation to achieve the greatest possible level of performance was an additional factor that undoubtedly affected the exercise test outcome. All of the subjects had invested many years and considerable financial resources in flight training, purchase of personal aircraft, and aviation support facilities.

Identification of HRmax

A survey of the literature and prominent textbooks failed to reveal specific criteria for the identification of HRmax in clinical exercise tests that do not include measurement of VO2max. Several authors report HRmax data defined only as the highest rate observed in incremental exercise [16,27-30] without assurance that subjects performed at their maximal capacity. Others include indices of perceived exertion or a description of the subject's effort [17,31]. In the present study, maximal effort was assured by: 1). A high level of motivation, 2). Prior experience with rigorous, high-intensity training exercises, and 3). A pre-test discussion of the indications for exercise termination. The latter included the distinction between local and general muscular fatigue, identification of the rating of perceived exertion, and true indication of shortness-of-breath versus the expected hyperpnea of maximal exercise. The latter point was a critical element in the pre-test discussion because many patients confuse shortness-of-breath, or dyspnea-on-exertion, with exercise hyperpnea. This procedure resulted in a high index of reliability derived from test-retest comparisons of measured HRmax.

Some investigators identified HRmax as the heart rate at which VO2max is achieved [18,26]. However, the inclusion of peakVO2 or VO2max data does not, in every case, assure that HRmax is achieved. In some subjects, a plateau in the oxygen uptake rate with increasing work may not be observed, particularly if exercise is stopped due to pain in leg muscles or joints, perceived shortness-of-breath, or lack of motivation [32]. An observed peakVO2 may be construed as a true VO2max especially if a high respiratory exchange ratio and high rating of perceived exertion are achieved. In this case, the associated HR may be erroneously identified as maximal. Wasserman et al. [32], suggest that errors in HRmax identification may also occur because of a curvilinear HR/VO2 relationship at high work rates in patients with some types of heart disease. These authors explain that oxygen uptake rate may appear to level off, suggesting VO2max was achieved, while HR continues to increases.

Clinical Implications

In the present study, ten subjects, including the oldest subject for whom questions of fitness for flight and medical status may have been most critical, had a difference of 8 bpm or more between measured and age-predicted HRmax using 220 - Age (Figure 2). Whaley et al. [16], found a greater mean of individual differences of 19.9 +/-4.4 bpm in 166 healthy males. In their subjects, the traditional age-predicted HRmax was achieved at 89% of the measured HRmax. Pilots with CAD achieved age-predicted HRmax at 92-96% of the measured HRmax. Differences of this magnitude are sufficient to create significant errors in selecting an exercise end-point [15]. Termination of exercise at 100% of the age-predicted HRmax, calculated by 220 - Age, yields a test that falls short of the FAA's expectation, and the expectation of military aviation medical examiners, that the elicited cardiac response represents the true limit of performance. Tests terminated at HR that is not the true maxima may limit the opportunity to discover ischemia, incidence of ventricular ectopic complexes, dysrhythmia, and abnormal blood pressures.

Exercise prescriptions based on age-predicted HRmax using 220 - Age, rather than the measured HRmax, may regulate training activity substantially below the desired level in older subjects [15,16]. For example, a pilot aged 60 years may be given a target HR of 128 bpm derived from the calculation of 80% age-predicted HRmax. If his age-predicted HRmax were 12 bpm less than the measured rate, his target HR for training would be equivalent to 74% of the true HRmax. As a consequence, the metabolic intensity of training activities, particularly with regard to proximity to the anaerobic threshold, would be significantly less than desired [33-37]. Larger errors, and greater ambiguity, in exercise prescription is inferred by the data of Whaley et al. [16], for healthy males who demonstrated a 20 bpm difference between measured and age-predicted HRmax.

Differences in measured and the traditional age-predicted HRmax may also create substantial errors in fitness assessment. The subjects of the present study were able to exercise an average of one minute beyond the point at which age-predicted HRmax was reached. Some subjects exercised as much as 2.0 minutes beyond this point. If the test had stopped at 100% age-predicted HRmax, the exercise capacity, expressed in METs or estimate VO2max, would have been under-estimate by 10% or more. Whaley et al. [16], demonstrated larger errors in fitness assessments made with the YMCA submaximal cycle test. Their data, and the findings of the present study, suggest that any fitness test that relies on submaximal HR / work relationships extrapolated to a 220 — Age predicted HRmax will significantly under-estimate aerobic capacity in subjects older than 40 years of age. It follows that research designed to investigate the effects of life style changes, medications, altered environmental conditions, aging, acute or chronic illness on

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exercise performance should not rely on age-predicted HRmax derived with 220 - Age, or some percentage of it, as a basis of measurement.

Contemporary exercise testing equipment includes a computer program that calculates an estimated HRmax for the patient, or subject, when age is entered with other personal information. All systems surveyed by the author use 220 - Age as the default equation. It is suggested that exercising testing software should be created that allows practitioners install a variety of regression equations, such as those listed in (Table 4), appropriate to the subject's age, fitness status, and medical history.

Conclusion

The widely accepted, traditional equation for predicting HRmax in exercise significantly under-estimates the true maximal cardiac frequency in male pilots with heart disease. The accuracy of HRmax estimation in these subjects is not improved by using regression equations based on a meta-analysis of several hundred studies. The true HRmax pilots with CAD declines with age at a faster rate than that of healthy people.

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