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Commentary

THE SURPRISING HISTORY OF THE “HR_{max}=220-age” EQUATION

ROBERT A. ROBERGS AND ROBERTO LANDWEHR

Exercise Physiology Laboratories, The University of New Mexico, Albuquerque, NM

ABSTRACT

THE SURPRISING HISTORY OF THE “HR_{max}=220-age” EQUATION. **Robert A. Robergs, Roberto Landwehr. JEPonline.** 2002;5(2):1-10. The estimation of maximal heart rate (HR_{max}) has been a feature of exercise physiology and related applied sciences since the late 1930's. The estimation of HR_{max} has been largely based on the formula; HR_{max}=220-age. This equation is often presented in textbooks without explanation or citation to original research. In addition, the formula and related concepts are included in most certification exams within sports medicine, exercise physiology, and fitness. Despite the acceptance of this formula, research spanning more than two decades reveals the large error inherent in the estimation of HR_{max} (S_{xy}=7-11 b/min). Ironically, inquiry into the history of this formula reveals that it was not developed from original research, but resulted from observation based on data from approximately 11 references consisting of published research or unpublished scientific compilations. Consequently, the formula HR_{max}=220-age has no scientific merit for use in exercise physiology and related fields. A brief review of alternate HR_{max} prediction formula reveals that the majority of age-based univariate prediction equations also have large prediction errors (>10 b/min). Clearly, more research of HR_{max} needs to be done using a multivariate model, and equations may need to be developed that are population (fitness, health status, age, exercise mode) specific.

Key Words: Cardiovascular function, Estimation, Error, Exercise prescription, Fitness.

INTRODUCTION

This short manuscript has been written to provide insight into the history of the maximal heart rate (HR_{max}) prediction equation; HR_{max}=220-age. Surprisingly, there is no published record of research for this equation. As will be explained, the origin of the formula is a superficial estimate, based on observation, of a linear best fit to a series of raw and mean data compiled in 1971 (1). However, evidence of the physiological study of maximal heart rate prediction dates back to at least 1938 from the research of Sid Robinson (2).

Research since 1971 has revealed the error in HR_{max} estimation, and there remains no formula that provides acceptable accuracy of HR_{max} prediction. We present the majority of the formulae that currently exist to

estimate HRmax, and provide recommendations on which formula to use, and when. We also provide recommendations for research to improve our knowledge of the between subjects variability in HRmax.

THE IMPORTANCE OF MAXIMAL HEART RATE

Heart rate is arguably a very easy cardiovascular measurement, especially in comparison to the invasive or noninvasive procedures used to estimate stroke volume and cardiac output. Consequently, measurement of heart rate is routinely used to assess the response of the heart to exercise, or the recovery from exercise, as well as to prescribe exercise intensities (3). Given that the increase in heart rate during incremental exercise mirrors the increase in cardiac output, maximal heart rate is often interpreted as the upper ceiling for an increase in central cardiovascular function. Indeed, research for the last 100 years has demonstrated that heart rate does in fact have a maximal value (4); one that cannot be surpassed despite continued increases in exercise intensity or training adaptations.

Perhaps the most important application of the heart rate response to exercise has been the use of submaximal heart rate, in combination with resting and maximal heart rate, to estimate VO₂max. In many instances, maximal heart rate estimation is recommended by using the formula HRmax=220-age. Based on this application, heart rate responses to exercise have been used to calculate exercise intensities, such as a percent of maximal heart rate (%HRmax) or a percent of the heart rate reserve (%HRR) (Table 1).

Table 1: Use of heart rate to estimate exercise intensities that coincide with %VO₂max.

%VO₂max	% HR_{max}	%HRR*^
40	63	40
50	69	50
60	76	60
70	82	70
80	89	80
90	95	90

*based on Karvonen method (HR=HRrest + ((intended fraction) * (HR_{max} - HRrest)));
 ^%HRR equals the intended fraction expressed as %
 Adapted from Heyward V. (5) and Swain et al. (6)

HISTORY OF MAXIMAL HEART RATE PREDICTION

Due to our interest in improving the accuracy of maximal heart rate estimation, we have tried to research the origin of the formula HRmax=220-age (Tables 2 and 3). As far as we could determine from books and research, the first equation to predict maximal heart rate was developed by Robinson in 1938 (2). His data produced the equation HRmax=212-0.77(age), which obviously differs from the widely accepted formula of HRmax=220-age. As we will explain below, there are numerous HRmax prediction equations (Table 3), yet it is the history of the HRmax=220-age equation that is most interesting.

The Formula: “HRmax=220-Age”

Within textbooks, failure to cite the original research regarding the formula HRmax=220-age indirectly affirms a connection to Karvonen. This association exists due to the textbook presentation of HRmax prediction with the concept of a heart rate reserve, which was devised by Karvonen (3). Ironically, the study of Karvonen was not of maximal heart rate. To clarify, Dr. Karvonen was contacted in August of 2000 and subsequent discussion indicated that he never published original research of this formula, and he recommended that we research the work of Dr. Åstrand to find the original research.

Another citation for the formula is Åstrand (7). Once again, this study was not concerned with HRmax prediction. We were able to discuss this topic with Dr. Åstrand in September 2000 while he was in Albuquerque to receive his Lifetime Achievement Award in Exercise Physiology from the American Society of Exercise Physiologists. Dr. Åstrand stated that he did not publish any data that derived this formula. However,

he did comment that in past presentations he had stated that such a formula appears close to research findings, and would be a convenient method to use.

Interestingly, Åstrand published original HRmax data for 225 subjects (115 male, 110 female) for ages 4 to 33 years in one of his earlier texts (8). The data are from either treadmill or cycle ergometer exercise tests to VO₂max, with no knowledge of protocol characteristics. This data is presented in Figure 1a and b. When data for ages >10 years are used (Figure 1b), there is a significant correlation (r=0.43), yet considerable error (S_{xy}=11 b/min). The resulting formula is; HRmax = 216.6–0.84(age). Despite the similarity of the prediction equation to HRmax=220–age, the notable feature of this data set is the large error of prediction. Interestingly, in two other studies, Åstrand found that the average decrease in HRmax for women was 12 beats in 21 years (9) and 19 beats in 33 years (10). For men, the decrease in HRmax was 9 beats in 21 years (9) and ~26 in 33 years (10). If the formula HRmax=220–age is correct, the slope for HR decrement with increasing age would be 1. In addition, Åstrand’s data

Table 2: The research and textbooks, and the citations used or not used, in crediting the source of the HRmax=220–age formula.

<i>Publication</i>	<i>Year</i>	<i>Citation</i>
Research		
Engels et al.	1998	Fox & Haskell, 1971
O’Toole et al.	1998	ACSM. 1995
Tanaka	2001	Fox & Haskell, 1971
Vandewalle & Havette	1987	Astrand, 1986
Whaley et al.	1992	Froelicher,1987
Textbooks		
ACSM	2001	ACSM, 2000
Baechle & Earle	2000	No Citation
Baumgartner & Jackson	1995	No Citation
Brooks et al.	2000	No Citation
Fox et al.	1989	No Citation
Garret & Kirkendall	2000	No Citation
Heyward	1997	No Citation
McArdle, Katch & Katch	1996	Londeree, 1982
McArdle, Katch & Katch	2000	No Citation
Nieman	1999	No citation
Plowman & Smith	1997	Miller et al. 1993
Powers & Howley	1996	No Citation
Robergs & Roberts	1997	Hagberg et al, 1985
Robergs & Roberts	2000	No Citation
Roberts et al.	1997	Asmussen, 1959
Rowland	1996	No Citation
Wasserman et al.	1994	No Citation
Wilmore & Costill	1999	No Citation

a.

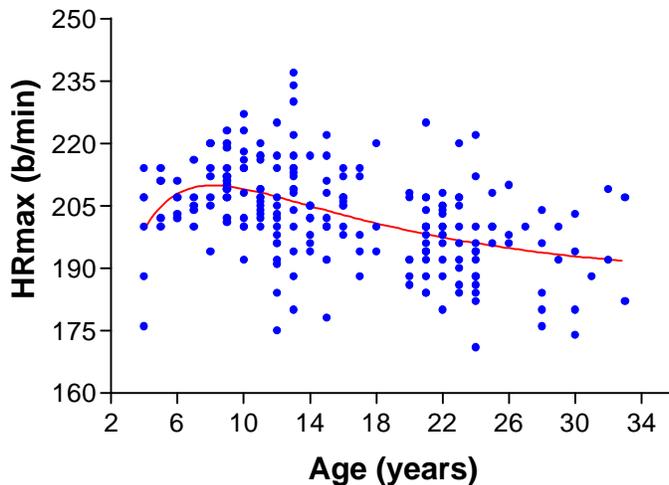


Figure 1: Data of HRmax for a) 225 subjects, 4 to 33 years, and b) a subset of the subjects, ages 11 to 33 years, n=196.

indicates that HRmax prediction from such formula should not be used on children 10 years or younger, as HRmax follows a different age associated change for children. In addition, the likelihood that children attain a true HRmax during exercise testing can be questioned.

It appears that the correct citation for the origin of $HR_{max}=220-age$ is Fox et al. (1). However, and as explained by Tanaka et al. (11), Fox did not derive this equation from original research. We evaluated the original manuscript of Fox et al. (1), which was a large review of research pertaining to physical activity and heart disease. In a section subtitled “Intensity”, a figure is presented that

b.

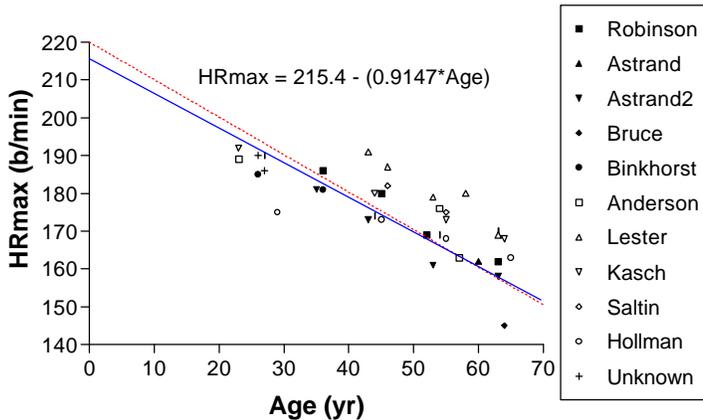
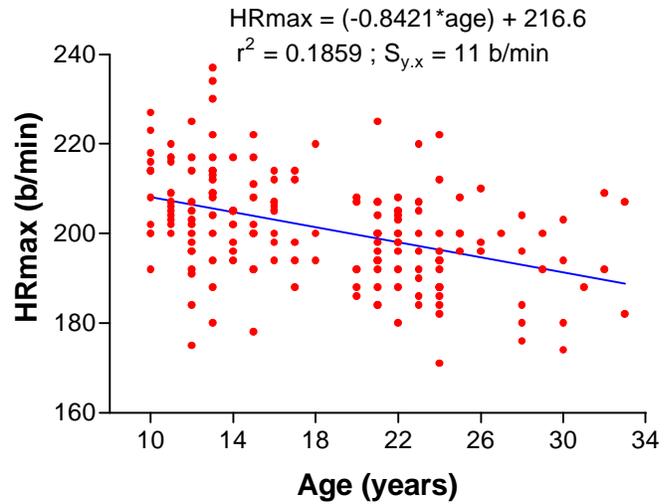


Figure 2. A reproduced figure from the data of Fox et al. (1) which was used to derive the original $HR_{max}=220-age$ formula. Blue line represents line of best fit. Red line represents $220-age$.

regression to the data set and derived the following equation; $HR_{max}=215.4 - 0.9147(age)$, $r=0.51$, $S_{y,x}=21$ b/min. Thus, even the original data from which observation established the $HR_{max}=220-age$ formula does not support this equation.

REVIEW OF RESEARCH OF MAXIMAL HEART RATE

We retrieved as much of the research on HRmax as is possible. This was a daunting task, as many of the original research and review studies on this topic did not provide complete references, or citations of the original research of this topic. We collated 43 formulae from different studies, and these are presented in Table 3, along with pertinent statistics when possible.

To verify if there was a trend towards the equation $HR_{max}=220-age$, we selected 30 equations from the ones presented in Table 3 (excluded equations derived from non-healthy subjects). The equations were used to recalculate HRmax for ages 20 to 100 years of age, and a new regression equation was calculated from the data (Figure 3). The regression equation yielded a prediction formula; $HR_{max}=208.754-0.734(age)$, $r=0.93$ and $S_{y,x}=7.2$, which is very close to that derived by Tanaka et al. (11) (Table 3).

contains the data at question, and consists of approximately 35 data points. No regression analysis was performed on this data, and in the figure legend the authors stated that;

“...no single line will adequately represent the data on the apparent decline of maximal heart rate with age. The formula maximum heart rate= $220-age$ in years defines a line not far from many of the data points..”

We decided to replicate the approach used by Fox et al (1), using the original data presented in their manuscript. As we could not find all manuscripts due to inaccurate citations, we reproduced the data from the figure and presented it in Figure 2. We fit a linear

Table 3. The known univariate prediction equations for maximal heart rate.

<i>Study</i>	<i>N</i>	<i>Population</i>	<i>Mean Age (range)</i>	<i>Regression (HRmax=)</i>	<i>r²</i>	<i>S_{xy}</i>
Univariate Equations						
<i>Astrand, in Froelicher (2)</i>	100	Healthy Men – cycle ergometer	50 (20 - 69)	211-0.922a	N/A	N/A
<i>Brick, in Froelicher (2)</i>	?	Women	N/A	226-age	N/A	N/A
<i>Bruce (12)</i>	1295	CHD	52±8	204-1.07a	0.13	22
<i>Bruce (12)</i>	2091	Healthy Men	44±8	210-0.662a	0.19	10
<i>Bruce (12)</i>	1295	Hypertension	52±8	204-1.07a	0.24	16
<i>Bruce (12)</i>	2091	Hypertension + CHD	44±8	210-0.662a	0.10	21
<i>Cooper in Froelicher (2)</i>	2535	Healthy Men	43(11 - 79)	217-0.845a	N/A	N/A
<i>Ellestad in Froelicher (2)</i>	2583	Healthy Men	42(10-60)	197-0.556a	N/A	N/A
<i>Fernhall (13)</i>	276	Mental Retardation	9-46	189-0.56a	0.09	13.8
<i>Fernhall (13)</i>	296	Healthy W & M	N/A	205-0.64a	0.27	9.9
<i>Froelicher (2)</i>	1317	Healthy Men	38.8(28-54)	207-0.64a	0.18	10
<i>Graettinger (14)</i>	114	Healthy Men	(19-73)	199-0.63a	0.22	N/A
<i>Hammond (15)</i>	156	Heart Disease	53.9	209-age	0.09	19
<i>Hossack (16)</i>	104	Healthy Women	(20-70)	206-0.597a	0.21	N/A
<i>Hossack (16)</i>	98	Healthy Men	(20-73)	227-1.067a	0.40	N/A
<i>Inbar (17)</i>	1424	Healthy W & M	46.7(20-70)	205.8-.685a	0.45	6.4
<i>Jones (18)</i>	100	Healthy W & M cycle ergometer	(15 – 71)	202-0.72a	0.52	10.3
<i>Jones N/A</i>	?	Healthy W &M		210-0.65a	0.04	N/A
<i>Jones (18)</i>	60	Healthy Women	(20-49)	201-0.63a		N/A
<i>Lester (19)</i>	48	W & M Trained		205-0.41a	0.34	N/A
<i>Lester (19)</i>	148	W & M Untrained	43(15 – 75)	198-0.41a	N/A	N/A
<i>Londeree (20)</i>	?	National Level Athletes	N/A	206.3-0.711a	0.72	N/A
<i>Miller (21)</i>	89	W & M Obese	42	200-0.48a	0.12	12
<i>Morris, in Froelicher (2)</i>	1388	Heart Disease	57(21 – 89)	196-0.9a	0.00	N/A
<i>Morris, in Froelicher (2)</i>	244	Healthy Men	45(20 – 72)	200 -0.72a	0.30	15
<i>Ricard (22)</i>	193	Treadmill W&M		209 -0.587a	0.38	9.5
<i>Ricard (22)</i>	193	W & M - cycle ergometer		200 -0.687a	0.44	9.5
<i>Robinson 1938 in Froelicher (2)</i>	92	Healthy Men	30(6 - 76)	212 -0.775a	0.00	N/A
<i>Rodeheffer (23)</i>	61	Healthy Men	25 - 79	214-1.02a	0.45	N/A
<i>Schiller 24)</i>	53	Women Hispanic	46(20-75)	213.7-0.75a	0.56	N/A
<i>Schiller (24)</i>	93	Women Caucasian	42(20-75)	207 -0.62a	0.44	N/A
<i>Sheffield (25)</i>	95	Women	39(19 - 69)	216 -0.88a	0.58	N/A
<i>Tanaka (11)</i>	?	Sedentary W&M		211 -0.8a	0.81	N/A
<i>Tanaka (11)</i>	?	Active W&M		207 -0.7a	0.81	N/A
<i>Tanaka (11)</i>	?	Endurance trained W&M		206 -0.7a	0.81	N/A

Study	N	Population	Mean Age (range)	Regression (HRmax=)	r ²	Sxy
Univariate Equations						
Tanaka (11)		Women & Men		208-0.7a	0.81	N/A
Whaley (26)	754	Women	41.3(14-77)	209-0.7a	0.37	10.5
Whaley (26)	1256	Men	42.1(14-77)	214-0.8a	0.36	10.7

W=women, M=men

Table 4. The known multivariate prediction equations for maximal heart rate.

Study and Equations	r ²
Londeree (20)	
$PMHR = 196.7 + 1.986xC2 + 5.361xE + 1.490xF4 + 3.730xF3 + 4.036xF2 - 0.00006xA^4 - 0.542xA^2$	0.77
$PMHRI = 199.1 + 0.119xAEF4 + 0.112xAE + 6.280xEF3 + 2.468xC2 + 3.485xF2 - 0.00006xA^4 - 0.591xA$	0.78
$PMHRC = 205 - 3.574xT1 + 8.316xE - 7.624xF5 - 0.00004xA^4 - 0.624xA^2$	0.85
$PMHRCI = 205 - 0.116xAEF3 - 0.223xAF5 + 0.210xAE + 6.876xEF3 + 2.091xC2 - 3.310xT1 - 0.0005xA^4 - 0.654xA$	0.86
$PMHR (National Collegiate Athletes) = 202.8 - 0.533xA - 0.00006xA^4$	0.73

PMHR=predicted maximal heart rate, C=Cross Sectional, I=interaction; a=A=age; A²=age; A⁴=(age⁴)/1000; C#=continent (if European, then C2=1, otherwise C2=0); E=ergometer (if treadmill, then E=1, if bicycle then E=0); F#=fitness level (if sedentary, F2=1, otherwise F2=0; if active then F3=1, otherwise F3=0, if endurance trained, then F4=1, otherwise F4=0; Type # =type of exercise protocol (if continuous and incremental, then T1=1, otherwise T1=0). Multiple letters interaction terms which should be multiplied together.

Interestingly, Londeree (20) developed a multivariate equation using the variables age, age², age⁴/1000, ethnicity, mode of exercise, activity levels, and type of protocol used to assess HR (Table 4). However, no statistical results pertaining to significant increases in the explanation of variance in HRmax using a multivariate model was provided by the authors. The same criticism applies to the study of Tanaka et al. (11). As Zavorsky (27) showed that endurance training lowers HRmax, and others have shown the exercise mode specificity of HRmax (28,29,30), an original study of HRmax using multiple independent variables is long overdue.

The data from research of HRmax are clear in showing the large error of HRmax prediction using just a y-intercept and slope when age is the sole independent variable. Furthermore, the results and regression equations need to be recognized as being mode-specific (28,29,30). It is unfortunate that the mode-specificity of HRmax prediction equations is not clearly addressed in textbooks of exercise physiology and exercise prescription. Finally, even a multivariate model of HRmax prediction and variance explanation does not reduce the error of HRmax prediction.

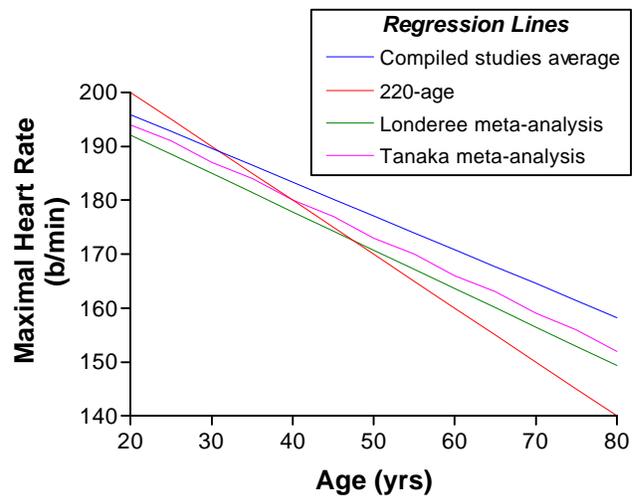


Figure 3. Regression lines from data obtained from 220-age, the mean of 30 studies from Table 3, and the meta analyses of Londeree (28) and Tanaka (47).

What is an Acceptable Error of HRmax Prediction?

Given the precision of HR measurement, the measurement error of HRmax is small and attributable to the exercise protocol and subject motivation. Consequently, HRmax measurement is likely to be accurate to within ± 2 b/min, if the subject truly attains maximal exertion. Nevertheless, another factor to consider is the impact of prediction error on the application of HRmax. For the estimation of two exercise intensities (Table 5), HRmax prediction errors (HRmax–predicted=error) of 2, 4, 6 and 8 b/min cause negligible error. For example, a HR of 150 b/min, which lies in the center of the “true” heart rate prescription range, remains within the recommended heart rate ranges for all error examples. However, as revealed in Table 3, errors in HRmax estimation can be in excess of 11 b/min. Consequently, it is likely that current equations used to estimate HRmax are not accurate enough for prescribing exercise training heart rate ranges for a large number of individuals.

Table 5. Estimations of error in submaximal exercise intensities and VO₂max when using HRmax estimated with errors of 2, 4, 6, and 8 b/min (underestimated prediction of HRmax).

Intensity	HR values For Given HRmax Error (True-Estimated, b/min (%))				
	True	2 (1)	4 (2.1)	6 (3.1)	8 (4.2)
<i>Submaximal exercise intensities</i>					
60-80% HRR	135-164	134-162	133-160	132-159	130-157
<i>VO₂max</i>					
YMCA* (mL/min)	4200	4083	6967	3850	3733
Error (mL/min)	0	117	233	350	467
Error (%)	0	2.8	5.6	8.3	11.11

Calculations are based on assuming a resting heart rate of 50 b/min, for a 25 year old person with a HRmax=192 b/min ; HRR=heart rate reserve ; for YMCA protocol, heart rates and workloads were assumed to be (HR:kgm/min) 90:150, 125:750, 153:1200, respectively.

When the prediction of HRmax is used in the estimation of VO₂max, as it is in the YMCA method, there can be considerable errors in estimated VO₂max (Table 5). For example, when HRmax is underestimated by 6 b/min, there is a resulting error in estimated VO₂max of 350 mL/min. This equates to an error of -8.3%, or -4.7 mL/kg/min for a 75 kg person.

The data of Table 5 help in selecting a suitable error in HRmax estimation. The error can be larger for purposes of prescribing training heart rate ranges than in the estimation of VO₂max. For purposes of prescribing training heart rate ranges, errors ≤ 8 b/min are likely to be acceptable. However, for VO₂max, it can be argued that prediction errors in HRmax need to be $< \pm 3$ b/min.

CONCLUSIONS AND RECOMMENDATIONS

Based on this review of research and application of HRmax prediction, the following recommendations can be made;

1. Currently, there is no acceptable method to estimate HRmax.
2. If HRmax needs to be estimated, then population specific formulae should be used. However, the most accurate general equation is that of Inbar (17) (Table 3); HRmax=205.8-0.685(age). Nevertheless, the error (S_{xy}=6.4 b/min) is still unacceptably large.
3. An acceptable prediction error for HRmax for application to estimation of VO₂max is $< \pm 3$ b/min. Thus, for a person with a HRmax of 200 b/min, error equals $\pm 1.5\%$. If this precision is not possible, then there is no justification for using methods of VO₂max estimation that rely on HRmax prediction formulae.

4. Additional research needs to be performed that develops multivariate regression equations that improve the accuracy of HRmax prediction for specific populations, and modes of exercise.
5. The use of HRmax is most prevalent in the fitness industry, and the people who work in these facilities mainly have a terminal undergraduate degree in exercise science or related fields. These students/graduates need to be better educated in statistics to recognize and understand the concept of prediction error, and the practical consequences of relying on an equation with a large standard error of estimate (S_{xy}).
6. Textbooks in exercise physiology and exercise prescription should contain content that is more critical of the HRmax=220-age or similar formulae. Authors need to stress the mode-specificity of HRmax, provide alternate, research substantiated formula, and express all content of items 1-5, above. Similarly, academic coverage of HRmax needs to explain how this error detracts from using HRmax estimation in many field tests of physical fitness and in exercise prescription.

Address for correspondence: Robert A. Robergs, Ph.D., FASEP, EPC, Director-Exercise Physiology Laboratories, Exercise Science Program, Department of Physical Performance and Development, Johnson Center, Room B143, The University of New Mexico, Albuquerque, NM 87131-1258, Phone: (505) 277-2658, FAX: (505) 277-9742; Email: robergs@unm.edu

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