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Age-predicted maximal heart rate in healthy subjects: The HUNT Fitness Study

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Maximal heart rate (HR_{max}) declines substantially with age, but the magnitude and possible modifying effect of gender, body composition, and physical activity are not fully established. The present study examined the relationship between HR_{max} and age in 3320 healthy men and women within a wide age range using data from the HUNT Fitness Study (2007–2008). Subjects were included if a maximal effort could be verified during a maximal exercise test. General linear modeling was used to determine the effect of age on HR_{max}. Subsequently, the effects of gender, body mass index (BMI), physical activity status, and maximal oxygen uptake were examined. Mean predicted HR_{max} by three former prediction formulas were compared with measured HR_{max} within 10-year age groups. HR_{max} was univariately explained by the formula 211 – 0.64·age (SEE, 10.8), and we found no evidence of interaction with gender, physical activity, VO_{2max} level, or BMI groups. There were only minor age-adjusted differences in HR_{max} between these groups. Previously suggested prediction equations underestimated measured HR_{max} in subjects older than 30 years. HR_{max} predicted by age alone may be practically convenient for various groups, although a standard error of 10.8 beats/min must be taken into account. HR_{max} in healthy, older subjects and women were higher than previously reported.

Maximal heart rate (HR_{max}) is commonly used in clinical exercise testing and to prescribe exercise intensity in training and rehabilitation programs. HR_{max} describes the highest heart rate achieved by a subject exercising to exhaustion and is verified by a plateau of heart rate despite increasing workload. In the literature, HR_{max} commonly refers to the peak heart rate at termination of a graded maximal exercise test (Tanaka et al., 2001; Gulati et al., 2010). However, in clinical settings, a maximal exercise test is not always feasible and there is a need to predict HR_{max} from age prior to testing to be able to adequately assess heart rate response and relative intensity of effort at submaximal levels. During diagnostic exercise testing, the test is commonly terminated and termed nondiagnostic if the subject reach a predetermined percentage of age-predicted HR_{max} without electrocardiography (ECG) signs of ischemia (e.g., 85% of predicted HR_{max}; Balady et al., 2004; Amsterdam et al., 2010). Moreover, sensitivity is reduced in tests not reaching the target heart rate, which seems to be true both in exercise ECG as well as in exercise in combination with imaging modalities (Cumming, 1972; Giannrossi et al., 1989; Iskandrian et al., 1989). While in exercise testing the predicted HR may be substituted with rate of perceived exertion (RPE) which may better ensure an adequate stress level, this is not the case in pharmacological stress (Pinkstaff et al., 2010). Despite great individual variability, the ability to reach a given percentage of age-predicted HR_{max}, an indication of impaired chronotropic competence, has a strong inverse association with coronary disease and mortality (Lauer et al., 1999; Dresing et al., 2000). Accordingly, establishing normal values for HR_{max} at certain age groups may be of great clinical importance.

HR_{max} at a given age is frequently estimated by the "220 – age" formula. This is usually implemented in nearly all commercial equipment for cardiac stress testing. However, the validity of this formula has often been questioned (Tanaka et al., 2001; Robergs & Landwehr, 2002; Brubaker & Kitzman, 2011). Another formula for age prediction of HR_{max}, based on a combined meta-analysis and a cross-validation in a sample of 514 healthy subjects, was proposed by Tanaka et al. in 2001. The formula 208-0.7·age yield more precise estimates of HR_{max} over a wide age range. More recently, Gulati et al. reported an overestimation of HR_{max} by the 220 − age formula in females referred for exercise testing and called for gender-specificity when incorporating parameters of HR response to exercise in clinical practice (Gulati et al., 2010). Others have proposed that factors such as body mass index (BMI), smoking, and physical activity status may also influence achievable HR_{max} (Miller et al., 1993; Zavorsky, 2000). However, most studies are limited by small or selected samples and lack of documentation of achieved exhaustion.

The aim of the present study was to develop a new prediction formula for HR_{max} through analysis of HR_{max} measured at VO_{2peak} in a diverse population of 4635 healthy subjects and compare this formula with three commonly used prediction formulas. Furthermore, we wanted to investigate the relationship between HR_{max} and gender, physical activity status, BMI, and objectively measured aerobic fitness.

Materials and methods

Study population

The participants of the present study were derived from the HUNT Fitness Study, a sub-study of a large, population-based health study in Nord-Trøndelag county, in the middle of Norway. The HUNT Fitness Study was designed to obtain normal values of maximal oxygen uptake (VO_{2max}) in a healthy, adult population. Inhabitants free from self-reported cardiovascular diseases, pulmonary diseases, cancer, hypertension, and physical disability, in three communities within the main HUNT study, were eligible for VO_{2max} testing ($n = 12\,609$). A brief medical interview was conducted prior to testing with a medical doctor evaluating if the subjects were eligible for maximal testing. None of the participants were on any medication considered to potentially affecting heart rate, including beta-blockers. The population is therefore considered apparently healthy. Between June 2007 and June 2008, 4635 participants (age range 19–89) accepted the invitation and completed the maximal exercise test. The HUNT Fitness Study participants were, on average, more physically active than the total HUNT population, but not different from the total healthy population in HUNT regarding age, blood pressure (systolic and diastolic), waist circumference, and blood glucose levels (Aspenes et al., 2011).

The study was approved by the Regional Ethical Committee for medical research and the Norwegian Data Inspectorate. All participants signed a document of informed consent.

Maximal exercise testing

Prior to the maximal testing, all participants carried out a warm-up period of approximately 10 min at an individualized treadmill speed. The warm-up included a brief introduction to treadmill walking or running and detailed instruction about the test procedure. Participants were then equipped with a facemask and heart rate monitor before entering the test treadmill. Oxygen uptake and heart rate were measured during an incremental, individualized treadmill protocol until exhaustion. All participants were encouraged to avoid hand-rail support. Oxygen uptake kinetics were measured directly by a portable mixing chamber gas analyzer (MetaMax II, Cortex, Leipzig, Germany) and heart rate was monitored continuously by radio telemetry (Polar S610, Polar Electro Oy, Kempele, Finland). Speed and/or inclination were increased gradually from the warm-up pace whenever the oxygen uptake flattened. An advantage of the individualized protocol with different initial workload levels is that, even in this heterogeneous population, all subjects could be brought to exhaustion within 8–12 min as recommended (Balady et al., 2010). A test was regarded maximal if the oxygen uptake did not increase more than 2 mL/kg/min despite increased workload, in combination with a respiratory exchange ratio above 1.05 and subjective rating of perceived exertion of 17 or above on the Borg 6–20 scale (Borg, 1974). Maximal heart rate was defined as the highest heart rate achieved at termination of a maximal test and consecutively noted in an individual test log. The test–retest reliability of maximal heart rate after maximal treadmill testing are provided by earlier studies and generally considered to be high (Froelicher et al., 1974; Bosquet et al., 2008). All tests were carried out by trained personnel and test equipment were routinely calibrated. Volume ventilation was calibrated every third test and gas every fifth. Ambient air measurement was automatically checked before each test.

Covariates

BMI was calculated as body weight in kilograms divided by the squared value of height in meters and classified according to the definition suggested by the World Health Organization ("Normal": <25; "Overweight": 25–29.9; "Obese": ≥30; World Health Organization, 2000). In total, 42.0%, 44.9%, and 13% of the participants were classified as normal, overweight, and obese, respectively. More men than women were considered overweight (56% vs 34% for men and women), while the percentage of obese participants were similar for both genders. Self-reported physical activity was classified according to the updated recommendations from the American College of Sports Medicine/American Heart Association as "Inactive" for less than once a week of self-reported activity, "Less than recommended" for less than 150 min/week of self-reported activity, and "Recommended activity" for 150 min or more per week of self-reported activity at moderate or high intensity (Haskell et al., 2007). Smoking status was self-reported and categorized as "Never smoked or quitted smoking" and "Daily or occasional smoker". Peak oxygen uptake was categorized as gender-specific tertiles (cut-off values, <32.0, 32.0–38.9, and ≥39.0 mL/kg/min and <40.0, 40.0–47.9, and ≥48.0 mL/kg/min for women and men, respectively).

Statistical procedures

Only subjects that fulfilled the criteria of a maximal test, with registered maximal heart rate (HR_{max}), were included in the analysis ($n = 3320$). General linear modeling was used to determine the effect of age on HR_{max}. HR_{max} was entered as the dependent variable and age as the independent variable. Nonlinearity of the relationship between age and HR_{max} was investigated by including polynomial terms to the regression model. In a subsequent analysis, the effects of gender, BMI, physical activity status, and maximal oxygen uptake were examined by entering these factors as independent variables in addition to age. In further subsequent models, interaction terms were included as well to assess effect modification. The continuous variables were checked for normality, homogeneity of variances, and heteroscedasticity of the residuals.

Validation of prior formulas was done by comparing mean predicted HR_{max} by the former formulas with measured HR_{max} within age groups. Age was categorized into 10-year age groups (i.e., 19–29 years, 30–39 years, . . . , 60–69 years, >70 years). Prediction error and total error by applying the different formulas to the present population were calculated for the total population and within subgroups of age. Prediction error was calculated as the

Table 1. Descriptive data for the total, male, and female participants

	Total	Men	Women
N	3320	1726	1594
Age (years)	46.1 ± 12.8	46.9 ± 12.8	45.3 ± 12.7
Anthopometrical data			
Height (cm)	173.2 ± 9.0	179.6 ± 6.3	166.2 ± 5.8
Weight (kg)	77.6 ± 13.6	85.3 ± 11.2	69.1 ± 10.8
BMI (kg·m^2)	25.8 ± 3.4	26.4 ± 3.1	25.0 ± 3.7
Smoking status (% yes/no)	22.5/77.5	22.7/77.3	22.4/77.6
Resting heart rate (beat/min)	59 ± 9.5	57 ± 9.1	60 ± 9.7
Treadmill data			
VO_{2max} (mL/kg/min)	41.8 ± 9.3	45.9 ± 8.9	37.3 ± 7.5
VO_{2max} (L/min)	3.24 ± 0.90	3.88 ± 0.71	2.55 ± 0.48
Maximal heart rate (beat/min)	182 ± 13.6	182 ± 14.1	182 ± 13.0
Heart rate difference (beat/min)	123 ± 15.3	125 ± 15.5	121 ± 14.8
Ventilation (L/min)	108.6 ± 9.6	129.2 ± 23.7	86.4 ± 16.3
RER	1.14 ± 0.05	1.14 ± 0.05	1.14 ± 0.05
Peak RPE	18 ± 0.96	18 ± 0.95	18 ± 0.96
Physical activity data (N)			
Inactive (%)	501 (15.1)	339 (19.6)	162 (10.2)
Less than recommended (%)	1999 (60.2)	958 (55.5)	1041 (65.3)
Recommended activity (%)	800 (24.1)	418 (24.2)	382 (24.0)

Abbreviations: N, number of subjects; SD, standard deviation; BMI, body mass index; VO_{2max}, maximal oxygen uptake, heart rate difference, maximal heart rate – resting heart rate; RER, respiratory exchange ratio; RPE, rate of perceived exertion on Borg 6–20 scale. "Recommended" and "less than recommended" activity were categorized according to the updated recommendations from American College of Sports Medicine/American Heart Association (2011). Treadmill data variables refer to maximal values during the test.

sum of predicted minus measured HR_{max} divided by the number of subjects. Total error was calculated as the squared of the difference divided by sample size [$\sqrt{\Sigma(\text{measured} - \text{predicted})^2/n}$].

All statistical analyses were performed with the PASW statistical package version 18.0 (Copyright 1993–2007 Polar Engineering and Consulting, Nikiski, AK, USA).

Results

In the present study, 3320 subjects (1594 women and 1726 men, age range 19–89 years) were included based on HR_{max} during a graded maximal treadmill test. Descriptive statistics of the population is presented in Table 1. HR_{max} was inversely and linearly related to age in the total sample expressed by the following regression equation:

$$HR_{max} = 211 - 0.64 \cdot \text{age}$$

Inclusion of polynomials did not improve on the fitness of the model. A standard error of the estimate of 10.8 beats/min demonstrated a substantial variation in HR_{max}, which was evident across the full age range.

Individual HR_{max} values with age for the total sample of men and women are presented in Fig. 1. Women had a statistically significant, although negligibly, lower HR_{max} adjusted for age (difference in women vs men, −1.4 beats/min, $P < 0.001$). Subjects reporting physical activity habits in accordance with the ACSM/AHA recommendations showed a slightly lower HR_{max} adjusted for age than the "Inactive" and "Less than recommended" activity groups (difference in "Recommended" vs "Inactive", −3.4 beats/min, $P < 0.001$). When we divided subjects into gender-specific tertiles of peak oxygen uptake, we found no age-adjusted differences in women ($P = 0.18$), while low-fit men (first tertile) showed a slightly lower HR_{max} than the most fit (third tertile, difference in low vs high fit, −2.4 beats/min, $P = 0.003$). Obese subjects (BMI ≥ 30) showed a modestly decreased HR_{max} compared with the overweight and normal weight groups (difference in "Obese" vs "Normal weight", −2.3 beats/min, $P < 0.001$). There was no statistical evidence for a difference in age-adjusted HR_{max} between smokers and nonsmokers ($P = 0.43$). A multivariate blockwise regression analysis revealed that age alone accounted for 36% of the explained variance (R^2, 0.36), while the inclusion of gender, physical activity, smoking, and BMI categories added virtually no contribution to the explained variance in the total population (R^2 change, 0.007). Inclusion of VO_{2peak} categories in gender-specific models or VO_{2peak} as a continuous variable in the full model did neither increase R^2 considerably.

Inclusion of interaction terms indicated that the rate of decline in HR_{max} by age was not significantly influenced by gender ($P = 0.16$), physical activity status ($P = 0.08$), smoking status ($P = 0.62$), or BMI ($P = 0.27$). The interaction between age and tertiles of VO_{2peak} was not significant among men ($P = 0.19$) or women ($P = 0.19$).

Validation of the previously suggested HR_{max} formulas showed that both the widely used equation initially proposed by Fox et al. (220 − age; 1971), the more recent equation by Tanaka et al. (2001), and the female-based

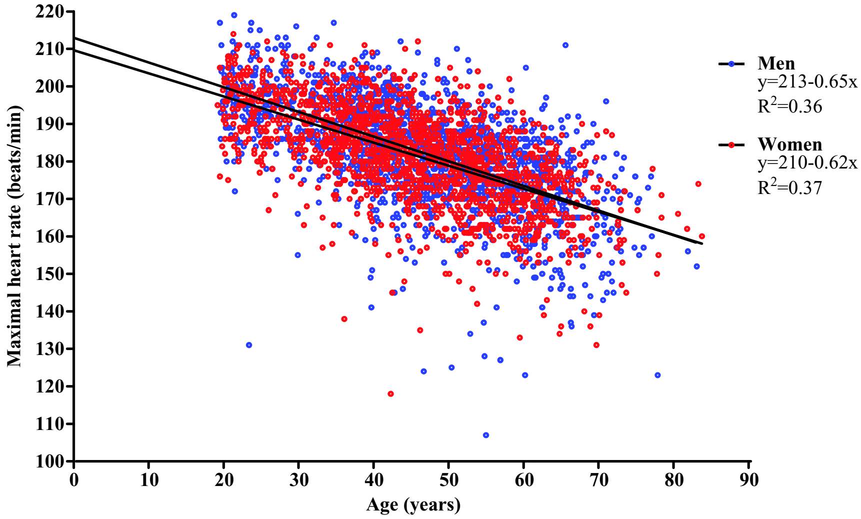

Fig. 1. Individual values and regression lines depicting the relation between maximal heart rate and age for men and women.

Table 2. Measured and predicted HR_{max} stratified by age in total sample

Age groups	HR_{max} (achieved)	HR_{max} (220 – age)	HR_{max} (Tanaka)	HR_{max} (Gulati)*	Peak RPE	Peak RER
19–29 (*n* = 399)	195 ± 9.9	195	191	184	19	1.16
30–39 (*n* = 687)	189 ± 10.1	184	183	175	18	1.15
40–49 (*n* = 923)	183 ± 10.9	175	177	167	18	1.14
50–59 (*n* = 795)	176 ± 11.6	165	170	158	18	1.14
60–69 (*n* = 440)	171 ± 12.3	156	163	150	18	1.13
70+ (*n* = 76)	164 ± 12.4	146	156	140	18	1.12

*Predicted scores from the female sample. ±, standard deviation from the mean.
HR_{max}, mean maximal heart rate; 220-age, predicted HR_{max} from the formula 220-age; Tanaka, predicted HR_{max} from 208·0.7 (age); Gulati, predicted HR_{max} from 206-0.88·age; RPE, rate of perceived exertion from the Borg 6–20 scale; RER, peak respiratory exchange ratio.

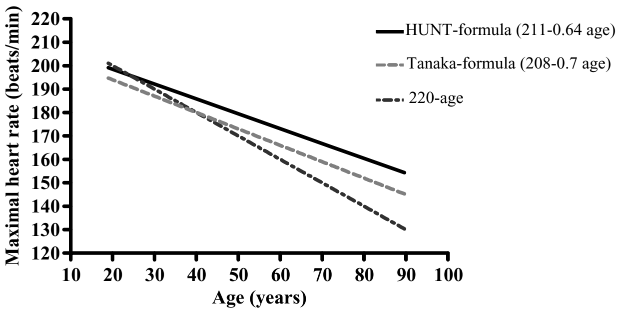

Fig. 2. Distribution of HR_{max} predicted by established formulas using HUNT Fitness Study data.

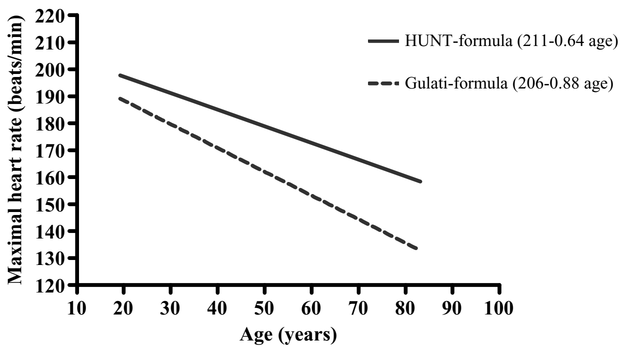

Fig. 3. Distribution of HR_{max} in the female sample predicted by the Gulati formula and the HUNT formula using HUNT Fitness Study data.

equation by Gulati et al. (2010) underestimated measured HR_{max} in the present population (Table 2, Figs 2 and 3). A tendency toward more substantial underestimation at older ages, particularly from the 220 – age equation and the Gulati equation, was indicated by the slopes of the regression lines and increasing prediction error within older age groups (Table 3). In our sample, 76.6% (2543) of subjects had a HR_{max} above the value calculated from the 220-age formula and 23.4% (777) did not reach the predicted value. Among those under 40 years of age, however, 60.9% had values above predicted HR_{max} from 220 – age, while the corresponding percentages for 40–60 years and above 60 years were 81.8% and 88.8%.

For the Tanaka formula (208 – 0.7·age), 74.3% of the subjects had HR_{max} above the predicted heart rate for

Table 3. Predicted HR_{max} and error statistics in the total sample stratified by age

Age groups	19–29 ($n = 399$)	30–39 ($n = 687$)	40–49 ($n = 923$)	50–59 ($n = 795$)	60–69 ($n = 440$)	70+ ($n = 76$)	Overall
211 – 0.64·age	196	188	183	176	171	164	182
Prediction error	–0.53	0.26	0.20	–0.08	–0.04	–0.77	0.00
Total error	12.6	7.5	8.3	10.3	13.7	27.0	10.8
220 – age	195	184	175	165	156	146	174
Prediction error	0.37	–4.56	–7.75	–11.09	–14.50	–17.37	–8.03
Total error	12.7	7.3	8.2	10.8	20.2	50.6	14.3
Tanaka	191	183	177	170	163	156	176
Prediction error	–4.28	–5.80	–6.32	–6.68	–7.33	–7.24	–6.21
Total error	12.0	7.5	7.9	9.6	15.2	29.7	12.6
Female sample	($n = 202$)	($n = 356$)	($n = 437$)	($n = 373$)	($n = 196$)	($n = 30$)	($n = 1594$)
211 – 0.64·age	196	188	183	176	171	164	182
Prediction error	–1.53	–0.49	–0.66	–0.59	–0.72	–0.04	–0.71
Total error	8.7	10.9	13.5	9.5	14.7	33.1	10.4
Gulati	184	175	167	158	150	140	166
Prediction error	–9.67	–13.45	–15.54	–17.95	–20.16	–23.47	–15.61
Total error	14.7	16.2	15.9	21.2	28.2	102.0	19.0

HR_{max}, mean maximal heart rate, 220 – age, predicted HR_{max} from the formula 220-age, Tanaka, predicted HR_{max} from 208 – 0.7 ·age, Gulati, predicted HR_{max} from 206 – 0.88·age, RPE, rate of perceived exertion from the Borg 6–20 scale, RER, respiratory exchange ratio. Prediction error = Σpredicted – measured HR_{max}/n; Total error = $\sqrt{\Sigma(\text{measured} - \text{predicted})^2}$.

their age. However, the percentage was quite stable across age groups as expected from the slopes of the regression lines ($\beta = -0.64$ in the present study and $\beta = -0.7$ in the study by Tanaka et al.) and the mean differences in 10-year categories were less than for the 220 − age equation, as shown in Table 3 (prediction error range 0–17 and 4–7 for the 220 − age and Tanaka equation, respectively).

Applying the female-based equation proposed by Gulati et al. to our female population showed the most substantial underprediction. As indicated in Table 3, the mean underprediction increased with age from −10 beats/min in the 20- to 29-year-old group to −23 beats/min among those above 70 years old.

Discussion

The present study presents normal values of maximal heart rate (HR_{max}) for 3320 healthy subjects across a wide age range with uniform maximal testing. HR_{max} was linearly and inversely related to age explained by the formula; 211 − 0.64·age (SEE = 10.8, $r = 0.60$). The standard error of the estimate is in accordance with numerous studies investigating the relationship between HR_{max} and age (Sheffield et al., 1978; Tanaka et al., 2001; Robergs & Landwehr, 2002; Wohlfart & Farazdaghi, 2003; Gulati et al., 2010). Moreover, our data suggest that HR_{max} at certain age groups may be higher than suggested by previous studies (Tanaka et al., 2001; Brawner et al., 2004; Gellish et al., 2007; Gulati et al., 2010; Zhu et al., 2010).

HR_{max} was adequately explained by age alone and we could not find evidence of interaction with gender, self-reported physical activity, smoking status, VO_{2peak} categories, or BMI categories. This finding is in line with many previous population-based studies (Fitzgerald et al., 1997; Tanaka et al., 2001; Gellish et al., 2007), but contrasts with others (Wohlfart & Farazdaghi, 2003; Whyte et al., 2008; Zhu et al., 2010). We found only small differences in age-adjusted HR_{max} across categories of VO_{2peak} and physical activity with all mean differences being within a few beats. However, that physically active subjects showed a slightly lower HR_{max} than the inactive counterparts is in accordance with previous studies (Zavorsky, 2000). Our finding that smoking status was not associated with mean HR_{max} was somewhat surprising as cigarette smoking is reported to be strongly associated with an attenuated HR response to maximal exercise in previous epidemiological studies (Lauer et al., 1997). A possible explanation could be that the present population was rather healthy and smoking may not have substantially affected the chronotropic ability of the subjects. The rate of decline of HR_{max} with age was similar also for normal weight, overweight, and obese subjects. Although obese subjects showed a slightly lower mean HR_{max}, the difference was not enough to propose separate equations for normal weight and obese subjects. While the percentage of obese participants was quite low, it still contained 578 subjects, which are considerably more than previous studies including obese participants (Miller et al., 1993; Franckowiak et al., 2011).

Validity of previously proposed equations

Our study confirms the findings of several large studies claiming that the long-lived 220-age prediction equation, originally derived by Fox et al. (1971), substantially underestimates HR_{max} with increasing age (Sheffield et al., 1978; Tanaka et al., 2001; Gellish et al., 2007).

Previous studies suggest that the 220 – age formula overestimates HR_{max} in young individuals, corresponds to actual HR_{max} around 40 years of age, and then increasingly underestimates objectively measured values (Tanaka et al., 2001; Gellish et al., 2007). In our study, however, the underestimation by applying the 220 – age formula starts already in the 30- to 39-year-old groups, while it seems to be rather accurate in the 20s. Among 60–69 year olds, the 220 – age formula yields a mean underprediction of 15 beats/min, which given a total error of the estimate of 20.2 may lead to a predicted value >35 beats/min below the actual attainable HR_{max} in certain subjects.

The findings in the present study are in close accordance with a study by Tanaka et al. which reported the association between HR_{max} and age to be 208 – 0.7·age (Tanaka et al., 2001). Their equation was based on a large meta-analysis and cross-validated in a laboratory-based study including 514 voluntary subjects and was approved by a longitudinal follow-up study (Gellish et al., 2007). However, a mean underprediction of 4–7 beats/min is evident also by applying their formula to the present data.

We could not confirm the findings of Gulati et al. (2010), who reported that women had lower HR_{max} than predicted from the 220 – age equation, which they inaccurately interpreted as a male-based standard. In their large-scale study of asymptomatic women, only 25% of the participants achieved 100% or more of their age-predicted HR_{max} from 220 – age. In our study, however, 75% of the female participants achieved 100% or more of their predicted value. In men, 78% achieved HR_{max} above this threshold, also indicating that the gender differences were minor. The study by Gulati et al. did not report indicative measures of maximal effort (e.g., rating of perceived exertion, respiratory exchange ratio or flattening of HR, or oxygen uptake kinetics) and it may be speculated that the use of a symptom-limited protocol resulted in the termination of the test before maximal effort was attained.

Clinical implications

A reasonable accuracy of age-predicted maximal heart rate is of major importance in a number of clinical settings. First, inability to increase HR to "normal" age-specific values, commonly termed chronotropic incompetence (CI), is increasingly appreciated as a risk factor for cardiovascular disease and mortality (Lauer et al., 1996, 1999; Nishime et al., 2000; Myers et al., 2007; Brubaker & Kitzman, 2011). However, the widespread use of the 220-age formula in predicting HR_{max} in clinical evaluation of CI may be bothersome. Given that multiple large-scale studies fail to validate the 220 – age formula in different populations, using this formula as a reference to "normal" response seems quite arbitrary. Accordingly, Gulati et al. (2010) found that CI defined as being ≥1 standard deviation below the population-specific mean HR_{max} was a stronger predictor of premature mortality than applying the 220 – age equation. Furthermore, clinical exercise tests are commonly termed "nondiagnostic" if the subject reaches a target heart rate, typically 85% of their age-predicted HR_{max} without signs of ischemia (Amsterdam et al., 2010). Consequently, underprediction of HR_{max} (i.e., by applying the 220 – age formula to older subjects) yields a great risk of a false negative result as a relatively high workload may sometimes be necessary to achieve an ischemic state of the heart (Cumming, 1972; Gianrossi et al., 1989; Iskandrian et al., 1989; Balady et al., 2004). Using 85% of 220 – age in our study would result in only 23.6% of the population reaching a target of 85% of their actual HR_{max}. Even using 100% of 220 – age would result in a substantial number of subjects not reaching 85% of their actual HR_{max}. As the individual variation is high, using 85% of our predicted value would still result in only about half of our study group reaching 85% of their real HR_{max}. Only using 100% of the predicted values as a target will result in nearly all subjects reaching at least 85% of their individual HR_{max}. Finally, in training and rehabilitation programs, recommended intensity of exercise is commonly prescribed to specific HR target zones, based on the linear association between HR and oxygen consumption. Prediction of HR initial to exercise may therefore result in a workload above, or more likely, below the intended exercise intensity, particularly if making use of some of the former formulas. Moreover, directly measured HR_{max} is clearly beneficial to age-predicted HR_{max} in most of the aforementioned settings and is recommended when practically possible.

Strengths and limitations

The main strengths of the present study are a population-based design including both genders across a wide age range. The treadmill protocol was designed to ensure a true maximal effort of the subjects by individual adjustment of workload (i.e., speed and inclination of the treadmill) in response to the oxygen uptake and heart rate kinetics. Nevertheless, the VO_{2max} criteria in the present study were not very strict and the test protocol was not designed to evaluate HR_{max} specifically, possibly resulting in some subjects not reaching a true HR_{max}. However, we tried different cut-off values for the peak Borg scale rating and RER, and found no improvement in the accuracy of prediction by increasing the cut-off values to Borg scale ≥18 and RER ≥1.10. Moreover, as the human heart rate response to exercise is assumed to plateau at a fixed maximum, and no other variables seemed to influence the relationship substantially, we believe that the high heart rate reported is an indication of a valid test procedure. We further speculate that the ability of the subjects to give a maximal voluntary effort, which may be influenced by exercise test procedure, subject motivation and physical ability, is the main reason for the differences in mean HR_{max} across population samples. It may also be a strength of the present study that the participants in this study were very fit, as indicated by high mean VO_{2max} values, as fit individuals may be more able and motivated to put forth a strenuous effort.

The cross-sectional design does not allow for examination of individual changes in HR_{max} over time. A longitudinal design may be superior to a cross-sectional design when aging effects are the main concern. However, for prediction of HR_{max} by age, individual changes with aging may be of less importance as long as the prediction is satisfactory. Two recent prospective studies have longitudinally examined the relationship between HR_{max} and age, both claiming that the rate of decline in HR_{max} with increasing age is best described as curvilinear rather than linear (Gellish et al., 2007; Zhu et al., 2010). The curvilinear relationship of HR_{max} to age is rarely confirmed in population-based cross-sectional studies, including this study (Inbar et al., 1994; Tanaka et al., 2001; Gulati et al., 2010). Nevertheless, Gellish et al. (2007) concluded that a linear model would be preferable to a less practically interpretable nonlinear model as they found only minor differences in model fit. The proposed regression equation was developed in the present material. Thus, it is (per definition) the best fit to the present data, compared with all other formulas. However, to statistically compare it with, i.e., the Tanaka formula, the material has to be validated in a different sample.

The population in the present study was free from cardiovascular disease, hypertension, and cancer and is thereby considered apparently healthy. The proposed regression equation may therefore not be suitable for some patients groups and previously suggested equations specifically determined for these groups may yield more accurate estimates (Fernhall et al., 2001; Brawner et al., 2004). More large-scale studies are also needed to confirm the HR-age relationship in obese subjects. However, our population is fairly comparable to the total healthy population in the HUNT study and may thereby be a reasonable reference to other predominantly healthy free-living populations.

Perspectives

Our results support several studies in demonstrating that the traditional 220-age formula is inappropriate in predicting HR_{max}, especially in older subjects. Furthermore, the rate of decline in HR_{max} with age was not influenced by gender substantially, physical activity status, maximal oxygen uptake, smoking, or body mass index, indicating that HR_{max} predicted by age alone may be practically convenient for various groups. However, a standard error of the estimate of 10.8 beats/min must be accounted for when applying the formula $211 - 0.64 \cdot \text{age}$ to clinical settings, and a maximal test may be preferable when possible.

Key words: maximum heart rate, HUNT, population sample, clinical testing.

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