Effect of Gender on Computerized Electrocardiogram Measurements in College Athletes

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Abstract

Background: Broad criteria for classifying an electrocardiogram (ECG) as abnormal and requiring additional testing prior to participating in competitive athletics have been recommended for the preparticipation examination (PPE) of athletes. Because these criteria have not considered gender differences, we examined the effect of gender on the computerized ECG measurements obtained on Stanford student athletes. Currently available computer programs require a basis for "normal" in athletes of both genders to provide reliable interpretation. Methods: During the 2007 PPE, computerized ECGs were recorded and analyzed on 658 athletes (54% male; mean age, 19 ± 1 years) representing 22 sports. Electrocardiogram measurements included intervals and durations in all 12 leads to calculate 12-lead voltage sums, QRS amplitude and QRS area, spatial vector length (SVL), and the sum of the R wave in V_5 and S wave in V_2 (RSsum). Results: By computer analysis, male athletes had significantly greater QRS duration, PR interval, Q-wave duration, J-point amplitude, and T-wave amplitude, and shorter QTc interval compared with female athletes (all $P < 0.05$). All ECG indicators of left ventricular electrical activity were significantly greater in males. Although gender was consistently associated with indices of atrial and ventricular electrical activity in multivariable analysis, ECG measurements correlated poorly with body dimensions. Conclusion: Significant gender differences exist in ECG measurements of college athletes that are not explained by differences in body size. Our tables of "normal" computerized gender-specific measurements can facilitate the development of automated ECG interpretation for screening young athletes.

Keywords: electrocardiography; cardiovascular risk; screening; athletics; preparticipation examination

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Introduction

Sudden cardiac death (SCD) in young athletes is a rare but tragic occurrence that demands an optimal strategy for preparticipation cardiovascular (CV) screening. All cardiology experts agree that the preparticipation examination (PPE) of competitive athletes should include a CV-oriented history and physical examination. However, the addition of a resting 12-lead electrocardiogram (ECG) to the PPE remains controversial. Based on the recognition that an abnormal ECG may enhance the sensitivity of the PPE to identify cardiomyopathies responsible for athletic deaths, the ESC consensus statement recommends that the PPE should include a resting 12-lead ECG.[1] This proposal largely derives from the experience in Italy, where a screening program for competitive athletes has been implemented since 1982 and has been updated prospectively.[2] Recently, our group has demonstrated the cost efficacy of adding an ECG to the PPE.[3] The European Society of Cardiology (ESC) published criteria for "abnormal" ECGs that exclude athletes from competition unless they complete further CV evaluation; however, these criteria do not consider gender-specific ECG abnormalities even though gender differences in the ECGs have been reported in both athletes and nonathletes.[4] The landmark study of gender differences in athletes was published several decades ago and relied on visual measurements.[5] We present the voltages in spatial terms because the individual ECG leads are affected by body morphology, but we also considered the traditional left ventricular voltages used for estimating left ventricular hypertrophy.[6] Previously, we described our experience adding the ECG to the 2007 PPE of Stanford undergraduate student athletes relying on visual analysis.[7] In this article, we present the effect of gender on computerized ECG measurements. Our goal was to provide "normal" computerized gender-specific measurements to facilitate the development of automated ECG interpretation for screening young athletes.

Methods

Study Population

The target population was undergraduate Stanford students planning to compete in intercollegiate sports. To participate in the intercollegiate program at Stanford University, all athletes must complete an annual Web-based PPE questionnaire regarding personal (medical, CV, surgical, and athletic) history and family medical/CV history. In the next step, athletes must pass a physical examination by Stanford physicians who have the results of the questionnaires. During the PPEs in 2007, the student athletes were offered an ECG. An ECG was added according to a protocol approved by the Stanford Institutional Review Board, and written informed consent was obtained from all athletes. More than 95% of the athletes agreed to participate in the ECG screening. Computerized ECGs were recorded and analyzed on 658 athletes (54% male; mean age, 19 ± 1 years) representing 22 sports.

The 22 different sporting disciplines included: football, basketball, crew, sailing, golf, water sports (including swimming, water polo, synchronized swimming, and diving), field sports (including lacrosse, field hockey, baseball, softball, and soccer), racquet sports (including squash and tennis), floor sports (including gymnastics and wrestling), court sports (including volleyball and fencing) and track/field (including track/field and cross-country).

Electrocardiogram Analysis

During the 2007 PPE, ECGs were recorded using Schiller ECG machines by supervised and trained volunteers on all consented athletes, and digital recordings were entered into a database (SEMA, Schiller AG, Baar, Switzerland). The ECGs were also over-read by cardiologists who entered the visual interpretation and selected visual measurements into the StudyTRAX™ (ScienceTRAX, LLC, Macon, GA) database using a standardized form.

This investigation was designed as an observational study of ECG findings in college athletes without the intent to validate the role of the ECG as a screening tool for CV disorders in young athletes. Only athletes judged to have significant abnormalities by the senior investigator (VF) were recommended to undergo further testing, which included echocardiography and/or cardiac magnetic resonance imaging (MRI; n = 63). However, this suggested additional work-up was elective.

Computerized ECG measurements included all intervals and durations in 12 leads. Values considered out of range were re-read visually and corrected; waveform measurement algorithms most often failed for the P wave and T wave end. Intervals/durations are presented in milliseconds, and amplitudes are presented in millivolts. P- and T-wave and QRS complex voltages are represented in spatial constructs. The traditional left ventricular voltages used for estimating left ventricular hypertrophy were also considered as described in the following algorithms:

- RSsum;
- 12-lead voltage sum for QRS amplitude;
- 12-lead voltage sum for QRS area (QRS area for each lead was calculated as: [(Q amplitude × Q duration)/2 + (R amplitude × R duration)/2 + (S amplitude × S duration)/2); QRS area for all 12 leads was summed to obtain 12-lead voltage sum for QRS area); and
- Spatial vector length (SVL) for P-wave, T-wave and QRS complex (Figure 1). This calculation was used because it represents the maximal electrical energy generated by the heart and obviates the need to consider individual leads.

Other ECG parameters included PR interval, QRS duration, QTc interval, P axis, QRS axis, and T axis. ST-segment elevation of ≥ 2 mm in leads V_1 or V_2 was coded because it is a prerequisite for the Brugada syndrome pattern, and inverted T waves in V_2 and/or V_3 were coded because of their association with arrhythmogenic right ventricular dysplasia/cardiomyopathy (ARVD/C).

Data were analyzed using NCSS Statistical Software (NCSS, Kayesville, UT) and Statgraphics® (StatPoint Technologies, Inc., Warrenton, VA). Differences between the groups were compared using both unpaired t tests and nonparametric test and χ^2 tests for continuous and discrete variables, respectively. Because most of the ECG measurements were non-Gaussian distributed, all data are presented as medians and the inter-

Figure 1. Spatial vector length (SVL) calculations used for P-wave, T-wave, and QRS amplitudes in order to optimally represent the maximal electrical energy generated by the heart obviating the need to consider individual leads.

SVL for QRS:

$$\sqrt{(\text{R ampl in } V_2)^2 + (\text{R ampl in } V_5)^2 + (\text{S ampl in a VF})^2}$$

SVL for P wave:

$$\sqrt{(\text{P max ampl in } V_2)^2 + (\text{P max ampl in } V_5)^2 + (\text{P max ampl in a VF})^2}$$

SVL for T wave:

$$\sqrt{(\text{T max ampl in } V_2)^2 + (\text{T max ampl in } V_5)^2 + (\text{T max ampl in a VF})^2}$$

quartile range (IQR), a measure of statistical dispersion, being equal to the difference between the third and first quartiles. Unlike the total range, the IQR is a robust statistic, having a breakdown point of 25%, and is thus often preferred to the total range. Half of the IQR equals the median absolute deviation (MAD); this also facilitates setting boundaries for risk of being "abnormal." Correlations were determined using Pearson's product moment correlation. Correlations were calculated between the demographics and key ECG variables to identify relationships that could be considered for normalizing ECG measurements. Age was not chosen because of the narrow age range in this population. Forward stepwise multiple regression analysis was used to determine important predictors of ECG measurements. The independent variables considered were gender, height, weight, and body mass index (BMI). *P* values of < 0.05 were considered statistically significant.

Results

Height, weight, and BMI were greater in male compared with female athletes (Table 1). There was no difference in the percentage of ethnicities represented in each gender, with nearly 75% of both male and female athletes being Caucasian. In addition, we did not find significant differences in the major ECG abnormalities between ethnicities. Detailed information regarding the sports in which the athletes participated relative to gender is presented in Table 2. Percentage of male and female athletes was not significantly different across different sport disciplines except for sports restricted to men (football and wrestling).

Normal ECGs were found in 52% of females and only 20% of males. Visual analysis by 2 experienced cardiologists found no significant difference in the prevalence of abnormal ECGs between the races represented in our sample.[7] Furthermore, detailed analysis of the computerized measurements, including those considered in this article, failed to demonstrate any clinical meaningful differences between races. QRS duration and PR interval were significantly higher, while QTc duration was significantly lower in male versus female athletes (Table 3). The results were the same after excluding athletes with right bundle branch block (n = 8) and Wolf-Parkinson-White syndrome (n = 2). Q-wave duration in leads I, aVF, and V_5 were significantly greater in male compared with female athletes. Q-wave amplitude in leads I and V_5, J-point amplitude in V_1, V_2, and V_5, and T-wave amplitude in aVF, V_2, and V_5 were also significantly greater in male compared with female athletes. No athletes had Q waves of $>$ 25% of the R wave or reached 40 ms duration; 5 athletes had Q waves of $\geq$ 4 mm in other than aVR or aVL, and 18 athletes had $\geq$ 4 mm isolated Q waves in aVL associated with right axis deviation.

The voltage algorithms calculations for the P and T waves and QRS complex are presented in Table 4. The RSsum and 12-lead voltage sums for R-wave amplitude, QRS amplitude, and QRS area were significantly greater in males compared with females. In addition, SVL for the QRS complex and T wave was significantly greater in males versus females, while

Table 1. Demographic Characteristics of the Collegiate Athletes Participating in the 2007 PPE at Stanford University

Variable	Total		Male		Female		*P* value	*P* trend
	Median (n = 658)	IQR	Median (n = 358)	IQR	Median (n = 300)	IQR	T test	Chi square
Age (y)	19	18–20	19	18–21	19	18–20		
Ethnicity (n [%])								0.015
Caucasian	484 (74)	–	253 (71)	–	231 (77)	–		
Hispanic	43 (7)	–	26 (7)	–	17 (6)	–		
African American	67 (10)	–	48 (13)	–	19 (6)	–		
Asian and Pacific Islander	64 (10)	–	31 (9)	–	33 (11)	–		
Height (in)	70	66–74	73	71–75	66	64–69	< 0.001	
Weight (kg)	73	63–86	83	74–92	63	57–69	< 0.001	
BMI (kg/m^2)	23.2	21–25	24.3	22–26	22.1	20–24	< 0.001	

Abbreviations: BMI, body mass index; IQR, interquartile range; PPE, preparticipation evaluation.

Table 2. Major Sports Participated in by Gender

Sport	Total (N)	Males (n)	Females (n)
Basketball	18	9	9
Football	64	64	0
Water sports	102	54	48
Crew	68	30	38
Sailing	13	4	9
Field	138	64	74
Squash and tennis	28	7	21
Gymnastics and wrestling	64	45	19
Court	39	23	16
Track and field	62	26	36
Golf	16	9	7
Total	612	335	277

no difference was noted in P-wave SVL. Figure 2 illustrates 3 of the measurement differences found between genders.

ST-segment elevation of ≥ 2 mm in leads V_1 or V_2 (requiring visual assessment to rule out Brugada syndrome pattern) was present in 22% of male versus 2% of female athletes ($P < 0.001$). No athlete exhibited the type 1 pattern specific for Brugada syndrome. There was no significant gender difference (5.5%) in T-wave inversion in leads V_2 or V_3.

The Pearson product moment correlations between anthropomorphic variables and QRS findings are shown in Table 5 separately for males, females, and total population. Height and weight were modestly correlated with QRS duration in all subjects (r = 0.45 and 0.38, respectively) and T-wave SVL (r = 0.40 and 0.30, respectively), but only weakly correlated with both variables in female and male populations separately. Thus, the significant correlations for QRS duration and height observed in the total population were due to gender differences. All other correlations were weak and nonsignificant. The QRS voltage algorithms all correlated well with one another (> 0.62), while the correlations with and between the P- and T-wave algorithms were weak.

The results of regression analysis of selected ECG measurements by gender, with height and BMI as the independent

Table 3. Electrocardiogram Data in Male and Female Athletes

Variable	Total		Male		Female		*P* Value
	Median (n = 658)	IQR	Median (n = 358)	IQR	Median (n = 300)	IQR	Mann-Whitney U Test
Major durations/intervals (ms)							
PR interval	154	140–172	156	142–172	151	137–170	0.045
P-wave duration	100	92–108	104	96–112	100	86–106	< 0.001
QRS duration	94	88–102	100	94–106	88	83–94	< 0.001
QTc	401	385–417	393	379–408	410	397–424	< 0.001
Axis (°)							
P axis	54	40–64	54	41–64	53	40–63	0.288
QRS axis	79	66–88	79	64–89	79	69–87	0.938
T axis	47	34–57	47	33–58	44	35–56	0.855
P-wave amplitudes (mv)							
Greatest positive in II, aVF	0.12	0.08–0.15	0.12	0.08–0.15	0.12	0.08–0.15	0.428
Q waves							
Duration V_5 (msec)	16	8–20	18	10–22	14	0–18	< 0.001
Duration aVF (msec)	16	0–21	16	0–22	14	0–20	0.001
Amplitude V_5 (mv)	–0.07	–0.12 to 0.03	-0.08	–0.14 to 0.03	–0.06	–0.11 to 0	< 0.001
Amplitude aVF (mv)	–0.07	–0.12 to 0	–0.07	–0.12 to 0	–0.06	–0.12 to 0	0.255
J amplitude/ST level (mv)							
aVF	0.01	–0.01 to 0.03	0.01	–0.01 to 0.03	0.01	–0.01 to 0.03	0.287
V_1	0.04	0.02–0.07	0.06	0.04–0.08	0.02	0.01–0.04	< 0.001
V_1^1	0.10	0.06–0.15	0.14	0.1–0.19	0.06	0.04–0.09	< 0.001
V_5^2	0.02	–0.01 to 0.04	0.02	0–0.05	0.01	–0.01 to 0.04	0.015
RS-wave amplitudes (mv)							
R wave aVF	1.26	0.94–1.57	1.31	1.0–1.62	1.20	0.92–1.5	0.007
R wave max V_5 or V_6	1.76	1.4–2.15	1.95	1.55–2.33	1.56	1.28–1.95	< 0.001
S wave max V_2 or V_3	–0.97	–1.25 to 0.68	–1.05	–1.42 to 0.76	–0.86	–1.13 to 0.52	< 0.001
T-wave amplitude (mv)							
aVF	0.26	0.18–0.34	0.28	0.18–0.36	0.24	0.17–0.32	0.002
V_2	0.43	0.26–0.66	0.61	0.42–0.8	0.28	0.19–0.41	< 0.001
V_5^2	0.51	0.37–0.68	0.58	0.44–0.74	0.44	0.31–0.59	< 0.001

Abbreviation: IQR, interquartile range.

Table 4. Results of the Analysis of the Summation Algorithms and SVL Calculations Representing the Maximal Electrical Energy of the Levf Ventricle and Atria

Variable	Total		Male		Female		*P* Value
	Median (n = 658)	IQR	Median (n = 358)	IQR	Median (n = 300)	IQR	Mann-Whitney U Test
Summations							
R wave V_5 and S wave V_2 (mv)	3.3	2.7–4.1	3.8	3.13–4.4	3.0	2.43–3.51	< 0.001
R wave amplitude in the 12 leads (mv)	11.1	9.4–13.1	12.1	10.26–13.99	10.1	8.54–11.67	< 0.001
QRS amplitude in the 12 leads (mv)	18.5	16.0–21.61	20.4	17.93–23.18	16.4	14.5–18.54	< 0.001
QRS area in the 12 leads (mv × msec)	431	344.3–500.7	482	398.8–558.2	375	311.6–425.8	< 0.001
SVL (mv)							
R wave	2.81	2.29–3.31	3.03	2.58–3.54	2.54	2.11–2.93	< 0.001
P wave	0.14	0.11–0.17	0.15	0.12–0.17	0.14	0.11–0.17	0.131
T wave	0.77	0.59–1.04	0.91	0.75–1.14	0.63	0.49–0.78	< 0.001

Abbreviations: IQR, interquartile range; SVL, spatial vector length.

variables, are presented in Table 6. QRS duration differed significantly in men and women with regard to height ($P < 0.01$ and $P < 0.001$, respectively) but not for BMI. Men demonstrated a 0.82-ms increase in QRS duration per inch in height, while women showed a 0.71-ms increase per inch in height. QTc only showed a significant relationship in women relative to height, with a 0.88-ms decrease per inch ($P = 0.02$). In men and women, SVL was the only variable significantly related to BMI, but the relationship was inverse. Men and women displayed a 0.05- and 0.04-mV decrease respectively per unit BMI ($P < 0.001$ and $P = 0.002$).

In a multiple regression analysis using gender and anthropometric variables (height, weight, BMI), gender was the strongest independent predictor of all the ECG variables except QRS duration (where height was the strongest predictor) and SVL P wave (where BMI was the strongest predictor). The variance explained in each of the models ranged from 2% to 24%. Gender was chosen as a significant independent predictor

Figure 2. Gender differences in QRS duration, QTc, and the sum of the S wave in V_2 and the R wave in V_5.

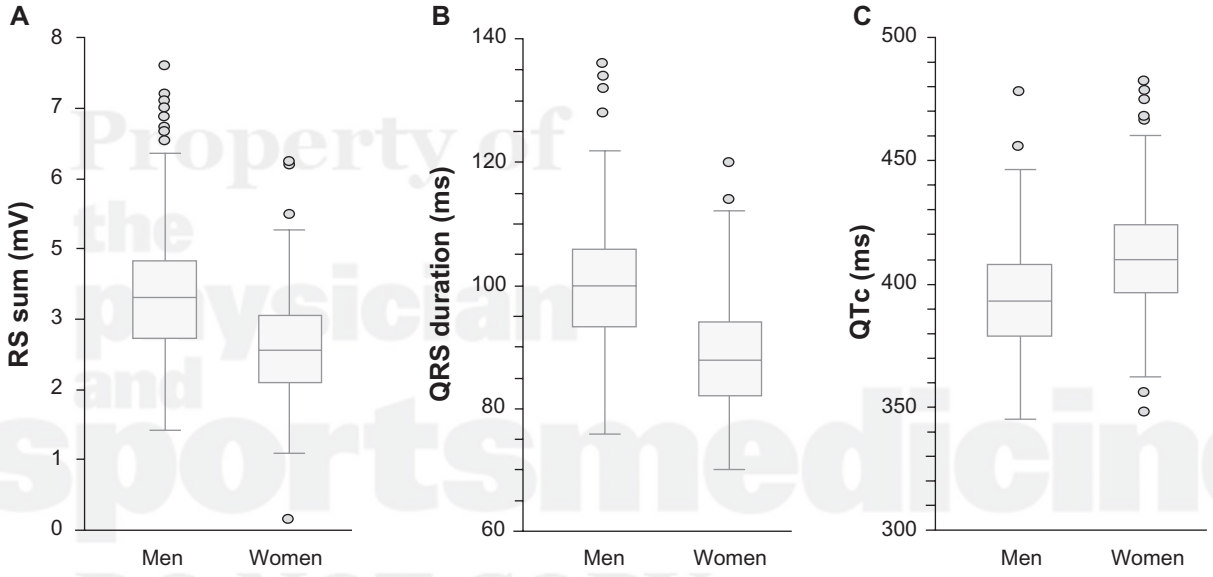

Table 5. Correlation Matrix of Body Characteristics and Measurements of Major Durations and Maximal Electrical Energy of the Left Ventricle and Atria

	Height	Weight	BMI	QRS Duration	QTc	QRS SVL	Sum R Wave Amplitude	QRS Area Sum	Sum R Wave V_5 and S Wave V_2	P-Wave SVL	T-Wave SVL
Total population											
Height	1.00	0.76	0.29	0.45	–0.24	0.24	0.17	0.16	0.25	0.01	0.40
Weight	0.76	1.00	0.84	0.38	–0.16	0.09	0.11	0.13	0.12	–0.06	0.30
BMI	0.29	0.84	1.00	0.20	–0.04	–0.06	0.03	0.08	–0.02	–0.10	0.11
QRS duration	0.45	0.38	0.20	1.00	0.01	0.18	0.17	0.16	0.19	–0.01	0.38
QTc	–0.24	–0.16	–0.04	0.01	1.00	–0.22	–0.13	–0.14	–0.24	0.10	–0.29
QRS SVL	0.24	0.09	–0.06	0.18	–0.22	1.00	0.74	0.69	0.96	0.22	0.47
QRS area sum	0.16	0.13	0.08	0.16	–0.14	0.69	0.85	1.00	0.62	0.15	0.34
Sum R wave V_5 and S wave V_2	0.25	0.12	–0.02	0.19	–0.24	0.96	0.67	0.62	1.00	0.19	0.51
P-wave SVL	0.01	–0.06	–0.10	–0.01	0.10	0.22	0.20	0.15	0.19	1.00	0.08
T-wave SVL	0.40	0.30	0.11	0.38	–0.29	0.47	0.37	0.34	0.51	0.08	1.00
Males											
Height	1.00	0.63	0.19	0.27	0.07	–0.06	–0.14	–0.09	–0.07	–0.02	0.08
Weight	0.63	1.00	0.88	0.16	0.11	–0.22	–0.20	–0.11	–0.18	–0.13	0.00
BMI	0.19	0.88	1.00	0.05	0.09	–0.24	–0.17	–0.08	–0.19	–0.16	–0.05
QRS duration	0.27	0.16	0.05	1.00	0.20	–0.01	0.00	0.02	0.00	–0.13	0.18
QTc	0.07	0.11	0.09	0.20	1.00	–0.14	–0.04	–0.07	–0.14	0.09	–0.26
QRS SVL	–0.06	–0.22	–0.24	–0.01	–0.14	1.00	0.69	0.69	0.96	0.27	0.37
QRS area sum	–0.09	–0.11	–0.08	0.02	–0.07	0.69	0.85	1.00	0.64	0.15	0.27
Sum R wave V_5 and S wave V_2	–0.07	–0.18	–0.19	0.00	–0.14	0.96	0.64	0.64	1.00	0.24	0.40
P-wave SVL	–0.02	–0.13	–0.16	–0.13	0.09	0.27	0.20	0.15	0.24	1.00	0.03
T-wave SVL	0.08	0.00	–0.05	0.18	–0.26	0.37	0.27	0.27	0.40	0.03	1.00
Females											
Height	1.00	0.62	–0.14	0.21	–0.14	0.10	0.01	–0.01	0.10	–0.06	0.20
Weight	0.62	1.00	0.68	0.17	–0.02	–0.07	0.00	0.04	–0.09	–0.14	0.05
BMI	–0.14	0.68	1.00	0.03	0.11	–0.18	0.00	0.06	–0.20	–0.11	–0.11
QRS duration	0.21	0.17	0.03	1.00	0.18	0.05	0.03	0.05	0.04	0.03	0.26
QTc	–0.14	–0.02	0.11	0.18	1.00	–0.08	0.01	–0.02	–0.11	0.17	–0.02
QRS SVL	0.10	–0.07	–0.18	0.05	–0.08	1.00	0.72	0.61	0.94	0.17	0.37
QRS area sum	–0.01	0.04	0.06	0.05	–0.02	0.61	0.81	1.00	0.48	0.13	0.19
Sum of R wave V_5 and S wave V_2	0.10	–0.09	–0.20	0.04	–0.11	0.94	0.58	0.48	1.00	0.14	0.38
P-wave SVL	–0.06	–0.14	–0.11	0.03	0.17	0.17	0.19	0.13	0.14	1.00	0.10
T-wave SVL	0.20	0.05	–0.11	0.26	–0.02	0.37	0.19	0.19	0.38	0.10	1.00

Abbreviations: BMI, body mass index; IQR, interquartile range; SVL, spatial vector length.

of all major ECG intervals (QTc, QRS duration) and accounted for between 12% and 23% of variance in measures of conducted left ventricular and atrial electrical activity. Height was also a predictor of QRS duration, explaining 21% of the variation in this parameter.

Discussion

Major findings in the present study include evidence to support previously noted gender differences in the general population as well as novel findings in college athletes. In the present study, the significant gender differences included longer QRS duration, PR interval, and Q-wave duration in male athletes, and longer QTc interval in female athletes. Male athletes also had significantly greater J-point and T-wave amplitudes. All ECG indicators of left ventricular chamber size were significantly greater in male athletes, including SVL, 12-lead R-wave amplitude, QRS area, and the sum of the R wave in lead V_5 and S wave in lead V_2. It is important to mention that we also considered the common voltage criteria for both right and left ventricular hypertrophy.

Ethnicity can have an effect on the ECG in professional athletes. For instance, ECG abnormalities have been found to be more common in African Americans than in Caucasian football players.[8] In addition, ethnic differences in left ven-

Table 6. Selected ECG Measurements With the Results of Regression Analysis for Height and BMI as Independent Variables for Men and Women Collegiate Athletes

ECG Variable	Gender	Change Per Inch (Height)	Correlation (r)	*P* Value	Change Per Unit BMI	Correlation (r)	*P* Value
QRS duration (ms)	Men	+0.82	0.27	0.00	+0.14	0.05	0.35
	Women	+ 0.71	0.21	0.0002	+0.12	0.03	0.64
QTc (ms)	Men	+0.50	0.08	0.13	+0.53	0.09	0.08
	Women	– 0.88	–0.14	0.02	+0.91	0.11	0.07
SVL (mv)	Men	–0.01	–0.06	0.26	–0.05	–0.24	0.00
	Women	+0.02	0.1	0.09	–0.04	–0.18	0.002

This analysis was performed to demonstrate if these variables effect ECG measurements such that the ECG criteria should be adjusted by them.
Abbreviations: BMI, body mass index; ECG, electrocardiogram.

tricular remodeling have been reported between African/Afro-Caribbean and Caucasian highly trained athletes.[9] In our sample, we did not find African American athletes to exhibit more ECG abnormalities than other ethnic groups.[7] Also, in our study population, detailed analysis of the computerized measurements failed to demonstrate any clinical meaningful differences between the different races. The reason for the discrepancy between our studies is not clear. Perhaps differences in the ECG between races are more pronounced in professional athletes than in college athletes. However, in a small study population of college athletes, Crouse et al[10] found that ECG abnormalities were more common in African American football players compared with Caucasian football players.

We examined the effect of height, weight, and BMI on the ECG measurements for 2 reasons: first, to determine if gender differences were merely due to body size differences; and second, to determine if the measurements could be normalized by body size.[11] However, we found a poor correlation between the ECG measurements and body dimensions. For example, when examining correlations in Table 5, the relationship between height and QRS duration is relatively high for the total population ($r = 0.45$), but substantially decreases when considered by gender (males only: $r = 0.27$; females only: $r = 0.21$). In Table 6, height explains 21% of the variance in QRS duration, yet gender only explains 3%. This small variance in QRS duration explained by gender can be attributed to preexisting differences in height between males and females.

There are several possible reasons for the lack of association between anthropomorphic variables and surface potential. First, although there is a clear association between body size and heart mass, the association between heart mass and surface potential is more complex, primarily because thoracic impedance varies with body composition and body size. Thus, although larger subjects have the largest heart mass, they also have greater impedance because of a larger amount of tissue between myocardial surface and skin surface. This impedance also varies with body morphology, which is a possible reason why BMI was correlated with ventricular and atrial surface potential difference. Furthermore, Rudy[12] demonstrated mathematically that in some forms of left ventricular hypertrophy with normal cavity size, a cancellation effect may be present so that a hypertrophied heart exhibits normal surface voltages. All of the above led us to conclude that the ECG measurements could not be meaningfully normalized by body size.

Gender-Specific ECG Findings in Athletes

A number of studies have considered the ECG characteristics or distinctive abnormalities according to the gender of athletes. Storstein et al[5] examined the influence of gender on the resting 12-lead ECG in 617 female and 833 male athletes. Compared with male athletes, females had significantly higher heart rates, shortened conduction times (PR, ventricular activation time, and QRS) and a prolonged repolarization time (QTc). In addition, female athletes had decreased P-, Q-, and T-wave amplitudes as well as indices of right, septal, and left ventricular hypertrophy compared with males. ST elevations in precordial leads were lower in females than in males. Notching of R/S in leads V_1 and V_2 and incomplete right bundle branch block was less common in females compared with males. Our study confirmed all of these manually made measurements.

George et al[13] compared ECG and echocardiographic characteristics of endurance and resistance-trained female athletes and controls. Sinus bradycardia was observed in all endurance athletes and in 4 of 10 resistance-trained athletes. Electrocardiogram criteria were unreliable for the prediction of left ventricular enlargement. Both female resistance- and endurance-trained athletes exhibited a lesser degree of enlargement of left ventricular wall thickness and mass compared with male athletes.

Pelliccia et al[14] reported significant gender differences in ECG abnormalities in 1005 Italian national athletes from 38 different sports. A significantly larger proportion of male athletes had either distinctly (17% vs 8%) or mildly abnormal (28% vs 14%) ECGs compared with female athletes. Most female athletes showed normal ECGs (78%) as compared with male athletes (55%), and male athletes had greater maximum R- or S-wave voltages and more frequently exhibited abnormal Q waves.

Clinical ECG Studies in Women

In 1960, Simonson et al[4] presented their findings on differences in ECG characteristics of middle-age men (n = 424) and women (n = 142). The most significant difference was the shorter PR and QRS duration in women similar to our findings. They concluded that present normal standards derived from groups of men are not valid for women, but made little comment regarding precordial amplitude differences in this age group.

Surawicz[15] has noted gender differences in the ECG and the possibility of predicting gender and age from ECG. The typical male ECG could be differentiated from the typical female ECG by the following characteristics: 1) more ST elevation (ie, early repolarization), 2) shorter ST segment, 3) steeper slope of the ST segment, 4) steeper ascent of the T wave, and 5) higher T-wave amplitude.[16]

Male hormones are responsible for the shorter QT in men,[17] with gender differences decreasing with age.[18] Interestingly, in first- or second-degree relatives of patients with the congenital long-QT syndrome, the females in the group aged 18 to 40 years were at higher risk than were males and the opposite occurs in the Brugada syndrome.[19]

In 389 adults (277 females), Okin et al[20] examined gender differences in ECG voltages and QRS duration to differences in cardiac dimensions, body size, gender differences in test performance of ECG criteria for the detection of echocardiographic left ventricular hypertrophy. In individuals with and without LV hypertrophy, men had longer QRS duration, higher Cornell voltage, higher 12-lead sum of QRS voltage, and higher Cornel and 12-lead voltage-duration products compared with women. These differences remained significant after adjusting for the greater left ventricular mass, height, and weight in men compared with women. The authors argue for gender-specific ECG criteria for the detection of hypertrophy.

Rautaharju et al[21,22] evaluated hazard ratios for incident heart failure, coronary disease, as well as cardiac and all-cause mortality using Cox regression in participants of the Women's Health Initiative and the Cardiovascular Health Study during a 9-year follow-up. Repolarization abnormalities appeared to best predict heart failure, while QRS-T spatial angle and QRS voltage best predicted coronary disease. The relative risk of mortality for ECG abnormalities was the same in women as in men. We found similar results regarding prevalence and prognostic value for ECG abnormalities of male and female veterans.[23]

Computer Analysis of the ECG

Because more physicians are being requested to interpret the ECGs of athletes, and most commercially available ECG machines provide computer interpretation, it is important to acknowledge the limitations of these interpretations and to improve on them. To those of us experienced with this situation, the incorrect calls of "acute infarction" and the ignoring of Q waves consistent with hypertrophic cardiomyopathy are expected. Automated programs tailored to athletes would greatly facilitate adding the ECG to the PPE, and this will only occur if the range of normality is established.

Study Limitations

There are many distinctions regarding the characteristics of Stanford athletes, including racial distribution and the academic selection process that affect our sample, limiting our findings to other settings. However, our athletes represented the major collegiate sports and were equally distributed by gender (46% women). Furthermore, the significant gender differences that we report have been documented in other studies described above. Because we do not have additional test results on these athletes, our results could be influenced by occult CV diseases. Our analysis is dependent on one commercial computerized program, and different measurements could be possible with another program.

Conclusion

Consistent with previous studies, our data suggest that gender has significant impact on ECG measurements obtained in college athletes. In the present study, the significant gender differences included longer QRS duration, PR interval, and Q-wave duration, greater J-point and T-wave amplitudes in male athletes, and longer QTc interval in female athletes. All ECG indicators of left ventricular chamber size were significantly greater in male athletes, including SVL, 12-lead R-wave

amplitude, QRS area, and the sum of the R wave in V_5 and S wave in V_2. Regression analysis of the ECG measurements with the body dimensions as the independent variables led us to conclude that the ECG measurements could not be meaningfully normalized by body size and that the differences found were due to gender. These differences are further evidence of distinct physiological patterns in female compared to male athletes. Therefore, gender-specific criteria for abnormal ECG findings are necessary to facilitate a more effective approach to the ECG screening in young athletes.

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Conflict of Interest Statement

Sandra Mandic, PhD, Holly Fonda, MS, Frederick Dewey, MD, Vy-van Le, MD, Ricardo Stein, MD, ScD, Matt Wheeler, MD, Euan A. Ashley, MRCP, DPhil, Jonathan Myers, PhD, and Victor F. Froelicher, MD disclose no conflicts of interest.

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