Journal of Electrocardiology 56 (2019) 115–120

Contents lists available at ScienceDirect

Journal of Electrocardiology

journal homepage: www.jecgonline.com

Prolonged P wave duration is associated with right atrial dimensions, but not atrial arrhythmias, in middle-aged endurance athletes

K. Konieczny [a], L. Banks [b], W. Osman [a], M. Glibbery [b], K.A. Connelly [a,c], A.T. Yan [a,c], J.M. Goodman [b,d], P. Dorian [a,c,*]

[a] Faculty of Medicine, University of Toronto, Toronto, Ontario, Canada
[b] Faculty of Kinesiology and Physical Education, University of Toronto, Toronto, Ontario, Canada
[c] St. Michael's Hospital, University of Toronto, Toronto, Ontario, Canada
[d] Division of Cardiology, Mount Sinai Hospital, University of Toronto, Toronto, Ontario, Canada

ARTICLE INFO

Keywords:
Electrocardiogram
Aging
Filtered P-wave duration

ABSTRACT

Background: Atrial arrhythmias occur at a higher than expected prevalence amongst endurance athletes. Few studies have examined both atrial structure and arrhythmias in middle-aged endurance athletes. We examined the relationship between P-wave duration, atrial dimensions, and the presence of atrial ectopy in long-standing, middle-aged endurance athletes.
Methods: Middle-aged athletes with a minimum of 10 years of competitive endurance sport history and no history of structural heart disease or clinical atrial arrhythmias, had 12-lead ECGs to assess P-wave duration, signal-averaged ECGs (SAECG) to assess filtered P-wave duration, a 24 h Holter monitor to assess atrial ectopy, and echocardiography and cardiac magnetic resonance imaging to assess atrial structural characteristics.
Results: Amongst endurance athletes ($n = 104$; mean age $= 54 \pm 5$ years; 63% male), filtered P-wave duration on SAECG was correlated with P-wave duration on 12-lead ECG ($r = 0.36$, p, 0.0001), as well as with larger CMR-derived RA areas ($r = 0.30$, $p = 0.01$) and volumes ($r = 0.24$, $p < 0.05$). There was no correlation between filtered P-wave duration and any LA measures on imaging ($p > 0.05$). There was no correlation between the incidence of atrial ectopy (premature atrial contractions or atrial tachycardia) and any electrocardiographic or structural measures.
Conclusion: Longer filtered P-wave duration was associated with larger RA areas and volumes, without an increase in atrial ectopy.

Introduction

Atrial fibrillation (AF) represents the most common clinically significant arrhythmia; its prevalence increases with age, affecting nearly 10% of those over the age of 80 [1,2]. Although AF occurs most commonly in the context of structural heart disease, atrial arrhythmias including AF occur at a higher than expected prevalence in healthy endurance athletes [3–20], with AF incidence over 5-fold higher amongst athletes as compared with controls [21]. Atrial flutter also occurs with greater frequency amongst athletes than sedentary controls [19,22], though the data describing this relationship is less robust.

Atrial enlargement, consistently linked to AF by a mechanistically unclear association, is also frequently reported in endurance athletes [9,10,23], typically reflecting reversible, hemodynamically advantageous remodelling; however, exercise-induced atrial enlargement may also serve as a pro-arrhythmic substrate [5–9,11–16]. As a result, the association between the degree of atrial enlargement and the propensity to develop AF may be different in athletes versus non athletes.

Electrocardiographic changes occur in left atrial disease, including increased P-wave duration and increased P-wave depth in lead V1. These changes correlate with atrial enlargement and fibrosis, and may precede structural changes; as such, they predict an increased risk of atrial arrhythmia. In addition, atrial ectopy (premature atrial contractions, atrial tachycardia) is associated with concomitant AF or its future development [24]. This study sought to determine the relationship between P-wave duration, atrial size, and the presence of atrial ectopy in long-standing, middle-aged endurance athletes. We hypothesized that slower intra-atrial conduction, manifesting as increased P-wave duration, would be associated with larger atrial size and increased atrial ectopy or fibrillation in athletes with no history of arrhythmia.

* Corresponding author at: Division of Cardiology, St Michael's Hospital, 30 Bond Street, Toronto, Ontario M5B 1X1, Canada.
E-mail address: dorianp@smh.ca (P. Dorian).

https://doi.org/10.1016/j.jelectrocard.2019.07.002
0022-0736/

Furthermore, we anticipated that this association would be more marked in athletes with a higher long-term vigorous exercise burden, controlling for age and gender.

Methods

General study procedures

Middle-aged adults (45–65 years old) were recruited using local community advertisements. Eligible participants had a minimum 10-year history of year-round endurance exercise involving sub-elite training and competition (including half-marathons, full-marathons, long-distance cycling events of >100 km, and/or half- or full-ironman distance triathlons). All eligible participants provided written informed consent prior to study participation. Participants were asked to abstain from caffeine (12 h), alcohol (12 h), and exercise (24 h) prior to their study visit. All participants were assessed at the same time of day. Initially, a detailed medical and sport history was obtained, and physical examination was performed by a cardiologist. Participants were excluded from this study if they reported >4 h per week of resistance training, a relevant clinical history (including atrial fibrillation or flutter, coronary disease, valvular disease, syncope, heart failure, diabetes, asthma, thyroid disorder, chronic inflammatory disease), use of cardioactive and/or recreational drugs, or consumption of ≥5 units of alcohol per day. The study was approved by the institutional research ethics boards and was in full conformity with the Helsinki Declaration on the use of human participants.

Resting electrocardiogram (ECG)

A trained technician performed a resting 12-lead ECG and signal-averaged ECG to obtain the p-wave and filtered p-wave duration, respectively. Standard electrode placement was used. ECG and SAECG were recorded using a commercially available system (General Electric Marquette Medical Systems Inc., Milwaukee, Wisconsin, USA) with participants in a supine position. The p-wave duration from the 12-lead ECG was measured in triplicate by a single, trained observer, as was the amplitude of the negative deflection in lead V1. This was performed assuming the baseline to be the isoelectric line following the T-wave and preceding the onset of the p-wave, and measuring the distance between this baseline and the nadir of the p-wave. The mean filtered p-wave duration was calculated by the proprietary software from the system and was visually verified.

24-hour Holter monitoring

A continuous 24-hour ECG was obtained using an ambulatory Holter monitor (General Electric SEER-1000). Participants were instructed to perform activities of daily living, with the exception of exercise training. Data were verified for wear time and activity level, to ensure compliance. Tracings were assessed as per standard protocol, to identify and quantify presence of premature atrial and ventricular extrasystolic beats, and runs of tachycardia (e.g. three or more sequential premature beats). Incidence of ectopic beats was also logged by hour of day to assess diurnal distribution. Suspected episodes of atrial fibrillation were visually assessed and logged based on heart rate irregularity and absence of P-waves.

Cardiopulmonary exercise testing

Graded treadmill exercise testing was performed to exhaustion to assess maximal oxygen consumption (VO_{2max}) with expired gases collected using a metabolic cart (Moxus Modular VO_2 system, Applied Electrochemistry Inc., Pittsburgh, PA). VO_{2max} was determined by a plateau in oxygen consumption despite an increase in work rate, with secondary measures confirming maximal effort, including the attainment of age-predicted maximal heart rate and a respiratory exchange ratio of 1.15 or higher.

Resting echocardiogram

Echocardiographic images (Vivid 7; GE Healthcare, Canada; M4S probe) were acquired by a trained sonographer from standard parasternal, apical, and subcostal windows (frame rate: 60–80 frames per second) with participants positioned in the left lateral decubitus position on an imaging table (Model 96039, American Echo, Kansas City, MO). Images were acquired with ECG gating using a 3-lead ECG. A minimum of three cardiac cycles was captured and averaged for analysis. System settings were adjusted to produce an optimal signal-to-noise ratio and endocardial definition. Data were analyzed offline by a single trained observer using a commercially available proprietary workstation (EchoPAC, Version 7, GE Healthcare). Right atrial size was determined in the apical four-chamber view, using the single-view area-length method. The biplane area-length method was used to determine the 2D left atrial size. The proprietary software computed left atrial volume based on the tracing of the endocardial border in both the apical four- and two-chamber views. For each atrium, atrial maximum (RA_{MAX}, LA_{MAX}), minimum (RA_{MIN}, LA_{MIN}), and pre-contraction ($RA_{PRE\text{-}A}$, $LA_{PRE\text{-}A}$) volumes were derived. Passive emptying of each atrium was defined as the difference between the maximum and pre-contraction volumes. Active emptying of each atrium was defined as the difference between the pre-contraction and minimum volumes. Reservoir volume was defined as the difference between the maximum and minimum volumes. The total emptying fraction of the left atrium was calculated $[(LA_{MAX} - LA_{MIN})/LA_{MAX}]$, as were the passive $[(LA_{MAX} - LA_{PRE\text{-}A})/LA_{MAX}]$ and active emptying fractions $([LA_{PRE\text{-}A} - LA_{MIN}]/LA_{PRE\text{-}A})$, respectively. The same calculations were performed for the right atrium.

Cardiac magnetic resonance imaging and analysis

Cardiac morphology and resting function was assessed using high-resolution cardiac MRI (CMR). Participants were asked to refrain from exercise on the day of their scan. A resting CMR was performed using a 3.0 T MRI scanner (Siemens MAGNETOM Skyra 3.0 T with TIM and DOT technology) with a phased-array cardiac coil and retrospective vectorcardiographic gating. One of two blinded operators completed each scan. Steady-state free precession images were obtained during breath-holds at end-expiration, with the participant in the supine position. Late gadolinium enhancement (LGE) images were acquired approximately 10 min after gadolinium injection (0.1–0.2 mmol/kg; Multihance Bracco Diagnostic Inc. Princeton, NJ) using a 3D inversion recovery prepared, respiration navigated, ECG gated, gradient echo pulse sequence, with fat saturation. Cine images were acquired to obtain a contiguous transverse short-axis stack (slice thickness of 8 mm, no gaps) covering the RA and LA, from the base of the heart to the apex. Twenty-five images per cardiac cycle were obtained at the end-tidal breath hold.

CMR analysis was performed using commercially available software (CVi42; Circle Cardiovascular Imaging, Calgary, AB, Canada) by one observer (M.G.) blinded to subject identity. Simpson's slice summation method was used for volumetric assessment (summation of outlined areas * slice thickness). In all subjects, RA and LA maximum and minimum volumes were manually traced through delineation of the atrial endocardial borders in all cardiac phases. Both right and left atrial appendages were included, while the venae cavae and pulmonary veins were excluded. RA and LA maximum volumes were determined on the image immediately prior to ventricular diastolic filling, and immediately prior to the opening of the tricuspid and mitral valves, respectively. The RA and LA minimum volumes were determined on the image immediately following atrial systole, just following closure of the corresponding atrioventricular valve. A straight line was drawn

between the leading edge of the tricuspid or mitral valve annulus, to determine the atrioventricular plane in the RA and LA, respectively. The frames with maximal and minimal volumes were selected independently. Maximal and minimal volumes were used to calculate atrial stroke volume (maximal volume − minimal volume), and ejection fraction (stroke volume ∗ 100%/maximal volume).

The SAECG, 24-hour Holter, echocardiogram, and CMR were all interpreted independently of each other, and blinded to the participants' exercise history.

Statistical analysis

Descriptive statistics are reported as mean ± standard deviation (SD), given normal distribution. Pearson r correlation was performed to examine the individual factors associated with filtered P-wave duration on the SAECG. A linear regression model using a maximum likelihood algorithm for variable selection was used to determine the multiple factors associated with filtered P-wave duration on the SAECG. Statistical significance was determined a priori ($p < 0.05$). All analyses were performed using SAS software (version 9.4; SAS Institute, Cary, NC).

Results

Participant demographics

A total of 89 middle-aged, normotensive athletes (69% male) completed the study. According to patient reported exercise diaries, the average hours of exercise per week were 9.1 ± 4.4 h, consistent over a 10-year period. Heterogeneity in the cohort was attributed to the fact that runners, cyclists, and triathletes participated in the study. More objectively reflecting level of conditioning was the VO_{2max} measured, with average values above the 90th percentile (Table 1). None of the patients had known structural heart disease or arrhythmia. On standard 12-lead ECG, transthoracic echocardiography, and CMR assessment, there were no pathologic abnormalities noted. All atrial linear measures and areas were within normal range, as were indexed volumes (Table 1).

Electrocardiographic and Holter assessments

Holter monitoring revealed highly variable degrees of atrial ectopy (Table 1). No trends in diurnal distribution of ectopy were noted. No subject had sustained (>30 s) atrial tachycardia or atrial fibrillation. There was no correlation between P-wave duration, either on standard ECG nor SAECG, and ectopy (Fig. 1). The presence of non-sustained supraventricular or ventricular runs was not associated with CMR-derived atrial size or volume indices ($p = 0.05$ for all).

Electro-structural correlations

There were significant correlations between a longer SAECG filtered P-wave duration and longer 12-lead ECG P-wave duration ($r = 0.36$, $p < 0.0001$) (Fig. 2), older age ($r = 0.36$, $p < 0.0001$), higher BMI ($r = 0.24$, $p = 0.02$), as well as CMR-derived indices of RA maximum volume (indexed; $r = 0.24$, $p < 0.05$) and RA area as measured in 4-chamber views ($r = 0.30$, $p = 0.01$). Weaker correlations were present between

Table 1
Descriptive characteristics.

	Endurance athletes (all; *n* = 89)	Male endurance athletes (*n* = 61)	Female endurance athletes (*n* = 28)
Demographics			
Age, y	54 ± 5	54 ± 5	53
VO_2max, ml/kg/min	49 ± 8	50 ± 8	47 ± 7
Body mass index (BMI), kg/m^2	23 ± 3	24 ± 3*	22 ± 3
Body surface area (BSA), m^2	1.84 ± 0.20	1.94 ± 0.13#	1.63 ± 0.14
Resting systolic blood pressure, mm Hg	114 ± 15	119 ± 15#	104 ± 9
Resting diastolic blood pressure, mm Hg	74 ± 10	77 ± 9#	67 ± 10
Standard electrocardiographic (ECG) indices			
P-wave duration, ms	101 ± 19	105 ± 15*	92 ± 23
Positive amplitude, mm	0.05 ± 0.03	0.05 ± 0.04	0.05 ± 0.03
Negative amplitude, mm	0.05 ± 0.04	0.05 ± 0.04	0.04 ± 0.04
P wave length, mm	39 ± 25	44 ± 25*	29 ± 22
PR interval, ms	173 ± 28	179 ± 30*	155 ± 24
QRS duration, ms	95 ± 9	98 ± 8*	89 ± 8
QT interval, ms	447 ± 37	443 ± 38	456 ± 35
QTc interval, ms	407 ± 22	402 ± 22*	416 ± 20
Signal-averaged electrocardiographic (SAECG) indices			
Filtered p-wave duration, ms	135 ± 24	141 ± 20*	122 ± 26
Filtered QRS duration, ms	113 ± 8	116 ± 6#	106 ± 8
Holter monitor (n = 80; reported as median (interquartile range: q1, q3))			
Number of isolated atrial premature beats, beats per hour	19(8,47) n = 80	16(8,49) *n* = 55	23(8,37) *n* = 25
Number of atrial tachycardia runs, beats	0(0,1) n = 80	0(0,1) n = 55	0(0,2) n = 25
Number of beats in atrial tachycardia runs, beats	5(3,6) *n* = 33	5(3,6) *n* = 24	4(3,6) *n* = 9
Number of isolated ventricular premature beats, beats per hour	4(0,11) n = 80	4(1,10) n = 55	5(0,19) n = 25
Number of ventricular tachycardia runs, beats	0(0,0) n = 80	0(0,0) n = 55	0(0,0) n = 25
Number of beats in ventricular tachycardia runs, beats	4(3,5) n = 6	5(4,6) *n* = 4	4(3,4) n = 2

* denotes $p<0.05$, # denotes $p<0.0001$

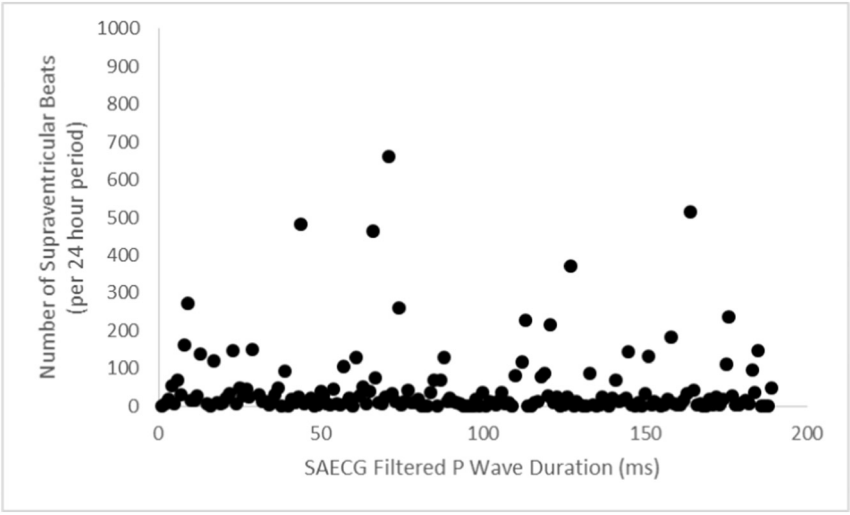

Fig. 1. Weak association between filtered P-wave duration and number of supraventricular beats.

longer SAECG filtered P-wave duration and echo-derived RA area during both systole and diastole ($r = 0.29$, $p = 0.007$; $r = 0.28$, p = 0.01, respectively), and indexed RA volume (r = 0.24, $p = 0.03$; $r = 0.22$, $p = 0.04$, respectively) at end-systole and end-diastole. There was no correlation between filtered P-wave duration and any LA measures of area or of volume by either CMR or echocardiography (Fig. 3).

In sex-based univariate analysis, males (vs females) had a higher body mass index, body surface area, and resting systolic and diastolic blood pressures, but no difference in age and VO_{2max}. On ECG assessment, males compared to females also had a longer P-wave duration, PR-interval, QRS duration, QTc interval, and SAECG filtered P-wave and QRS durations. On CMR assessment, no sex-related differences in atrial indices were observed, with the exception of males having a larger RA area and RA minimum indexed volume (Table 1).

Multivariable regression analysis examined the relationship between CMR-derived RA area and filtered P-wave duration, with age and sex selected as co-variables a priori. A greater RA area and older age were independently associated with longer filtered P-wave duration, while controlling for male sex (Table 2).

Discussion

In this study of sub-elite, middle-aged endurance athletes, a weak association was observed between standard ECG and SAECG P-wave parameters. There was no association observed between any electrocardiographic or structural measures, and atrial ectopy. Prolonged filtered P-wave duration on SAECG was associated with RA enlargement but not LA dimensions, as measured by CMR.

Electrocardiographic correlations

Although both standard surface and signal-averaged electrocardiography can be used to determine P-wave duration, they do so along different axes, with the potential to provide complementary, rather than confirmatory information. Furthermore, during acquisition of the SAECG, averaging of signals (thereby enhancing the signal to noise ratio) allows inclusion of very low-amplitude signals which would be overlooked on standard 12 lead ECG where such low-amplitude deflections would be masked by or attributed to artefact. Due to these

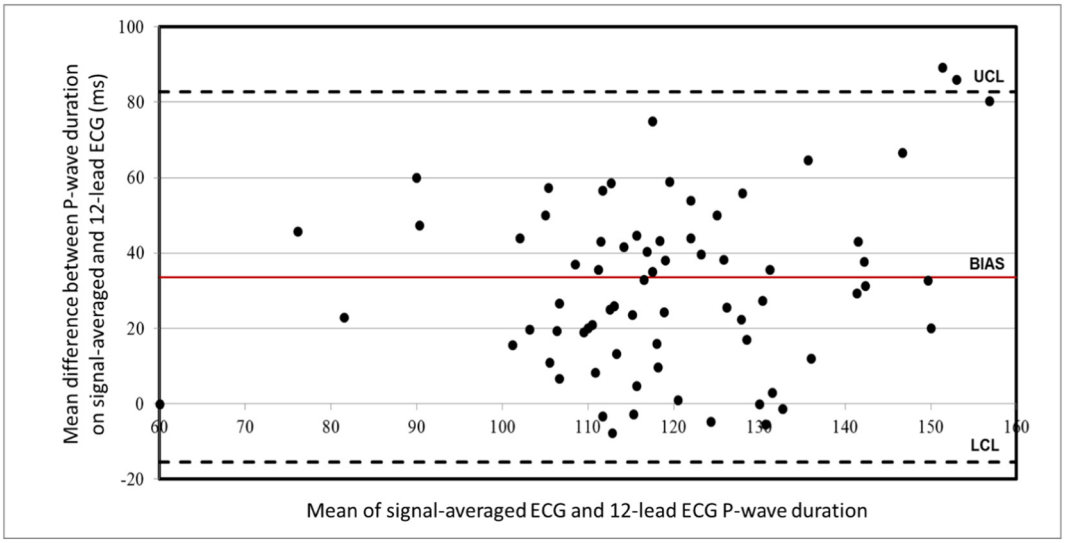

Fig. 2. Bland-Altman plot of P-wave duration on 12-lead ECG and signal-averaged ECG.

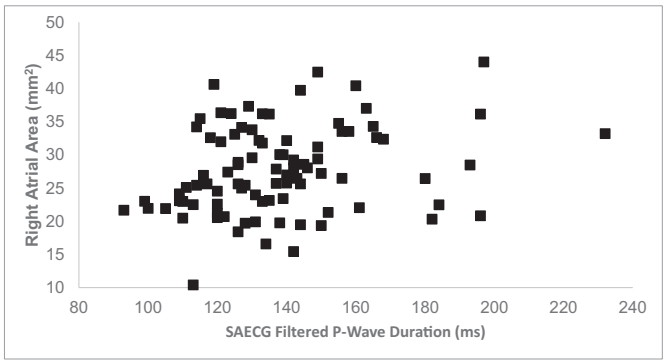

Fig. 3. Association between right atrial area on CMR and signal-averaged filtered P-wave duration ($r = 0.30$, $p = 0.01$).

differences, the modest correlation between standard ECG and SAECG is not entirely surprising. P-wave duration measured by SAECG was consistently longer than that obtained by standard 12-lead ECG.

With regard to atrial ectopy, 100% of subjects had any atrial ectopy, and 41% of subjects had runs of nonsustained atrial tachycardia. Sustained tachycardia was not noted in any subjects. It is possible that a longer duration of monitoring would have revealed a higher incidence of both atrial ectopy and sustained arrhythmia. In patients with no known history of sustained arrhythmia, 24-hour Holter monitoring would be expected to detect more frequent atrial events such as PACs. Neither the number of atrial ectopic beats per hour, nor the number of nonsustained atrial tachycardia events correlated with P-wave duration, either on surface ECG or SAECG (Table 1).

Associations between atrial electrical activity and structure

Prolonged filtered P-wave duration on SAECG was associated with RA enlargement but not LA dimensions, as measured by CMR. CMR is the gold-standard for quantifying cardiac chamber morphology. Not only is image quality maintained in the face of adjacent air-filled or bony structures, measurement is less operator-dependent. Moreover, volume determinations do not assume geometric assumptions and are therefore true 3D volumetric estimations. However, the utility of MRI is limited by longer acquisition time, cost, and incompatibility with ferromagnetic implants.

Increased LA size, exceeding indexed LA volumes of 34 mL/m2, as measured by echocardiography, has been demonstrated in a high percentage (67%) of athletes [25], prompting the European Association for Cardiovascular Imaging to advise that the upper limit of normal of the LA-anteroposterior diameter be increased to 45 mm and 50 mm in female and male athletes, respectively [10,26].

Although fewer studies have assessed the right-sided chambers in athletes, similar observations have been noted using CMR, and in both 3D and 2D echocardiography [27–31].

Zaidi et al. [32] have previously assessed right-sided chamber remodelling in young athletes, demonstrating consistently larger chamber sizes in athletes when compared with sedentary controls, regardless of ethnicity. BSA was found to be the strongest predictor of RV size; thus it was suggested that all RV measures be indexed accordingly and by extension, this recommendation was applied to measures of RA area.

Despite the emerging body of data assessing atrial size in athletes, there has been little published describing SAECG assessment of atrial depolarisation, particularly in athletes, where most studies have focussed upon the QRS complex. To our knowledge, no studies have described the relationship between P-wave measurement on SAECG and imaging parameters in athletes. The modest correlation observed suggests that the 12-lead ECG, SAECG, and MRI volumes are measuring different aspects of remodelling, which likely encompasses both structural and electrical alterations. Given that P-wave duration measures conduction time; it reflects both conduction velocity and the distance over which the depolarisation occurs. Conduction slowing in the atrium, producing longer P-wave duration, may be due to a combination of atrial electrical remodelling (due to ionic remodelling, gap junction remodelling, and changes in myocyte fibre orientation), in addition to atrial chamber enlargement.

Associations between intra-atrial conduction and atrial structural adaptations in endurance athletes

LA enlargement has been well-documented amongst endurance athletes, with changes noted within a year of consistent endurance exercise training [10,23,33–35], and to a lesser extent, reflecting the duration of intense training [10,34,36]. Atrial enlargement per se, is unlikely to induce a proarrhythmic state; where arrhythmia and atrial enlargement co-exist, there is likely some degree of atrial structural abnormality (such as increased collagen or interstitial edema), the latter perhaps manifesting as decreased atrial active emptying [37,38]. It is common to see left atrial enlargement, fibrosis and dysfunction amongst patients with AF.

A recent study by McNamara et al. demonstrated that 24 months of high-intensity exercise training induced structural changes in left-sided chambers, involving the LA more so than the LV, without inducing electrical changes as assessed by SAECG and Holter monitoring [39]. The right sided chambers were not assessed.

In contrast, the present study did not reveal structural LA abnormalities; however, increased RA areas and volumes correlated moderately with increased P-wave duration on SAECG. This is likely the result of P-wave duration being measured along three axes on the SAECG, which may allow some separation or distinction of the contribution of each atrium to the P-wave as a whole. On a standard 12-lead ECG, RA depolarisation is masked by that of the LA, which occurs with some temporal delay. With this in mind, it is of value to consider the possibility that P-wave duration may also reflect longer RA-to-LA depolarisation times, or that RA changes may be a marker for concomitant LA electrical remodelling resulting in prolonged depolarisation of both atria.

While a wealth of data clearly demonstrates that right-sided chamber enlargement remains a component of the “athlete's heart,” its relationship to arrhythmia has not been consistently established. Furthermore, whether or not RA remodelling has similar proarrhythmic effects to LA remodelling in athletes with AF remains to be determined. Both RA and RV dimensions are larger in elite endurance athletes, when compared with age- and sex-matched strength athletes and controls [27,40]. In this cohort, peak atrial longitudinal and contraction strain values were also reduced.

Table 2
Regression analysis of factors associated with filtered p-wave duration.

	Parameter estimate and standard error (EST[SE])	Confidence limits (95%)	*p*-Value
CMR-derived RA area (4-chamber), cm^2	0.9[0.4]	0.1,1.71	0.03
Age, y	2.1[0.4]	1.2,3.0	<0.0001
Male sex	6.0[5.9]	−17.4,5.5	0.31

Clinical implications

Although the geometric effect of RA volume loading may bear some similarity to pressure loading of the LA, one cannot presume that such effects on atrial function and structure at the microscopic level are comparable. Atrial fibrosis is difficult to objectively determine with current imaging technology, and electric remodelling, in the absence of invasive electrophysiologic studies, is similarly difficult to confirm. It remains unclear if prolonged P-wave duration in athletes represents chamber enlargement, slowed conduction velocity due to fibrosis or ion channel remodelling, or both.

Conclusion

Amongst amateur middle-aged endurance athletes, filtered P-wave duration on SAECG was correlated with RA size as measured by CMR. We speculate that this reflects a combination of both atrial electrical and structural remodelling.

Limitations

We focused on middle-aged adults with no prior history of cardiovascular disease. This represents a specific subject cohort; findings cannot be extrapolated to cohorts of patients with clinically apparent structural changes not observed in our data set. A short monitoring period was used, likely limiting sensitivity of arrhythmia detection. This, in addition to size of the cohort studied, may result in the study being underpowered to draw conclusions regarding significant electrostructural relationships. Larger studies involving longer-duration monitoring may be warranted to facilitate detection of less frequent arrhythmic events. A sedentary control group was not included in this study; nonetheless, normative values suggest that our cohort had physiologic remodelling likely reflecting a long-standing history of endurance exercise [34,35]. Future studies including exercising adults with atrial fibrillation are warranted.

In addition, the predictive value of observed changes on SAECG remains to be elucidated, and further studies would be required to investigate their significance.

Acknowledgements

This research study was funded by the Canadian Institutes of Health Research (funding reference number: 130477). Dr. KA Connelly is supported by a New Investigator Reward from the CIHR and an Early Researcher Award from the Ministry of Ontario. We would like to acknowledge Shin-Haw Lee, Ryan Sless, Vanessa Dizonno, and Tayler Buchan who assisted in data collection for this project.

References

[1] Karajlainen J, Kujala UM, Kaprio J, Sarna S, Viitasalo M. Lone atrial fibrillation in vigorously exercsising middle aged men: case-control study. BMJ 1998;316(7147):1784–5 Jun 13.
[2] Go AS, Hylek EM, Phillips KA, Chang Y, Henault LE, Selby JV, et al. Prevalence of diagnosed atrial fibrillation in adults: national implications for rhythm management and stroke prevention: the AnTicoagulation and Risk Factors in Atrial Fibrillation (ATRIA) Study. JAMA 2001;285:2370–5.
[3] Elosua R, Arquer A, Mont L, Sambola A, Molina L, Garcia-Moran E, et al. Sport practice and the risk of lone atrial fibrillation; a case-control study. Int J Cardiol 2006;108(3):332–7 Apr 14.
[4] Baldesberger S, Bauersfeld U, Candinas R, Seifert B, Zuber M, Ritter M, et al. Sinus node disease and arrhythmias in the long-term follow-up of former professional cyclists. Eur Heart J 2008;29(1):71–8 Jan.
[5] Molina L, Mont L, Marrugat J, BErruezo A, Brugada J, Bruguera J, et al. Long-term endurance sport practice increases the incidence of lone atrial fibrillation in men: a follow-up study. Europace 2008;10(5):618–23 May.
[6] Heidbuchel H, Anne W, Willmes R, Adriaenssens B, Van de Werf F, Ector H. Endurance sport is a risk factor for atrial fibrillation after ablation for atrial flutter. Int J Cardiol 2006;107(1):67–72 Feb 8.
[7] Myrstad M, Lochen M-L, Graff-Iversen S, Gulsvk AK, Thelle DS, Stigum H, et al. Increased risk of atrial fibrillation among elderly Norwegian men with a history of long-term endurance sport practice. Scand J Med Sci Sports 2014;114(8):1229–33 Oct 15.
[8] Andersen K, Farahmand B, Ahlbom A, Held C, Ljunghall S, Michaelsson K, et al. Risk of arrhythmia in 52,755 long-distance cross-country skiers: a cohort study. Eur Heart J 2013;34(47):3624–31 Dec.
[9] Mont L, Tamborero D, Elosua R, Molina I, Coll-Vincent B, Sitges M, et al. Physicial activity, height, and left atrial size are independent risk factors for lone atrial fibrillation in middle-aged healthy individiuals. Europace 2008;10(1):15–20 Jan.
[10] Pelliccia A, Maron BJ, Di Paolo FM, Biffi A, Quattrini FM, Pisicchio C, et al. Prevalence and clinical significance of left atrial remodelling in competitive athletes. J Am Coll Cardiol 2005;46(4):690–6 Aug 16.
[11] Drca N, Wolk A, Jensen-Urstad, Larsson SC. Atrial fibrillation is associated with different levels of physical activity at different ages in men. Heart 2014;100:1037–42.
[12] Mont L, Sambola A, Brugada J, et al. Long-lasting sport practice and lone atrial fibrillation. Eur Heart J 2002;23:477–82.
[13] Aizer A, Gaziano JM, Cook NR, et al. Relation of vigorous exercise to risk of atrial fibrillation. Am J Cardiol 2009;103:1572–7.
[14] Abdulla J, Nielsen JR. Is the risk of atrial fibrillation higher in athletes than in the general population? A systematic review and meta-analysis. Europace 2009;11:1156–9.
[15] Andersen K, Farahmand B, Ahlbom A, et al. Risk of arrhythmias in 52,755 long-distance cross-country skiers: a cohort study. Eur Heart J 2013;34:3624–31.
[16] Kwok CS, Anderson SG, Myint PK, Mamas MA, Loke YK. Physical activity and incidence of atrial fibrillation: a systematic review and meta-analysis. Int J Cardiol 2005;46:690–6.
[17] Kaiser-Nielsen LV, Tischer SG, Prescott EB, Rasmussen HK. Symptoms, diagnoses, and sporting consequences among athletes referred to a Danish sports cardiology clinic. Scand J Med Sci Sports 2017;27(1):115–23.
[18] Eijsvogels TM, Fernandez AB, Thompson PD. Are there deleterious cardiac effects of acute and chronic endurance exercise? Physiol Rev 2016;96:99–125.
[19] Baldesburger S, Bauersfeld U, Candinas R, et al. Sinus node disease and arrhythmias in the long-term follow-up of former professional cyclists. Eur Heart J 2008;29:71–8.
[20] Grimsmo J, Grundvold I, Maehlum S, Arnesen H. High prevalence of atrial fibrillation in long-term endurance cross-country skiers: echocardiographic findings and possible predictors – a 28–30 years follow-up study. Eur J Cardiovasc Prev Rehabil 2010;17:100–5.
[21] Karjalainen J, Kujala UM, Kaprio J, Sarna S, Viitasalo M. Lone atrial fibrillation in vigorously exercising middle aged men: a case-control study. BMJ 1998;316:1784–5.
[22] Hoogsteen J, Schep G, van Hemel NM, et al. Paroxysmal atrial fibrillation in male endurance athletes. A 9-year follow up, 6. Europace; 2004. p. 222–8.
[23] Wilhelm M, Roten L, Tanner H, Wilhelm I, Schmid JP, Saner H. Atrial remodelling, autonomic tone, and lifetime training hours in nonelite athletes. Am J Cardiol 2011;108:580–5.
[24] Gladstone DJ, et al. Atrial premature beats predict atrial fibrillation in cryptogenic stroke. Stroke 2015;46:936–41.
[25] Kou S, Caballero L, Dulgheru R, et al. Echocardiographic reference ranges from normal cardiac chamber size: results from NORRE study. Eur Heart J Cardiovasc Imaging 2014;15:680–90.
[26] Galderisi M, Cardim N, D'Andrea A, et al. The multi-modality cardiac imaging approach to the athlete's heart: an expert consensus of the European Association of Cardiovascular Imaging. Eur Heart J 2015;16(4) [353-353r].
[27] D'Andrea A, Riegler L, Golia E, et al. Range of right heart measurements in top-level athletes: the training impact. Int J Cardiol 2013;164:48–57.
[28] Hauser AM, Dressendorfer RH, Vos M, et al. Symmetric cardiac enlargement in highly trained endurance athletes: a two-dimensional echocardiographic study. Am Heart J 1985;109:1038–44.
[29] Scharhag M, Schneider G, URhausen A, et al. Athlete's heart: right and left ventricular mass and function in male endurance athletes and untrained individuals determined by magnetic resonance imaging. J Am Coll Cardiol 2002;40:1856–63.
[30] Scharf M, Brem MH, Wilhelm M, et al. Cardiac magnetic resonance assessment of left and right ventricular morphologic and functional adaptations in professional soccer player. Am Heart J 2010;159:911–8.
[31] D'Andrea A, Reigler L, Morra S, et al. Right ventricular morphology and function in top-level athletes: a three-dimensional echocardiographic study. J Am Soc Echocardiogr 2012;25:1268–76.
[32] Zaidi A, Ghani S, Sharma R, et al. Physiological right ventricular adaptation in elite athletes of African and Afro-Caribbean origin. Circulation 2013;127:1783–92.
[33] D'Andrea A, Riegler L, Cocchia R, et al. Left atrial volume index in highly trained athletes. Am Heart J 2010;159:1155–61.
[34] Brugger N, Krause R, Carlen F, et al. Effect of lifetime endurance training on left atrial mechanical function and on the risk of atrial fibrillation. Int J Cardiol 2014;170:419–25.
[35] D'Ascenzi F, Cameli M, Lisi M, et al. Left atrial remodelling in competitive adolescent soccer players. Int J Sports Med 2012;9:1389–91.
[36] Hoogsteen J, Schep GH, Van Hemel NM, An Der Wall EE. Paroxysmal atrial fibrillation in male endurance athletes. A 9-year follow up. Europace 2004;6:222–8.
[37] Toutouzas K, Trikas A, Pitsavos C, et al. Echocardiographic features of left atrium in elite male athletes. Am J Cardiol 1996;78:1314–7.
[38] Opondo MA, Aiad N, Cain MA, et al. Does high-intensity endurance training increase the risk of atrial fibrillation? A longitudinal study of left atrial structure and function. 2018;11:e005598.
[39] McNamara DA, Aiad N, Howden E, et al. Left atrial electromechanical remodelling following 2 years of high-intensity exercise training in sedentary middle-aged adults. Circulation 2018;0 [Published Online Nov 10, 2018].
[40] D'Ascenzi F, Cameli M, Padeletti M, et al. Characterization of right atrial function and dimension in top-level athletes: a speckle tracking study. Int J Cardiovasc Imaging 2013;29:87–94.