ORIGINAL ARTICLE

Post-exercise heart rate recovery and parasympathetic reactivation are comparable between prepubertal boys and well-trained adult male endurance athletes

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Abstract

Purpose This study tested the hypothesis that prepubertal boys, but not untrained men, would exhibit a similar post-exercise parasympathetic reactivation as well-trained adult male endurance athletes.

Methods Twelve prepubertal boys (12.3 ± 1.6 years), 14 untrained men (21.8 ± 2.2 years) and 16 well-trained adult male endurance athletes (24.5 ± 4.8 years) completed an incremental maximal run field test on a track. Immediately after exercise completion, heart rate recovery (HRR) was assessed in the supine position for 5 min. Heart rate variability was analyzed in the time domain, and log-transformed values of the root mean square of successive differences in heart beats (Ln $RMSSD_{30}$) were calculated over consecutive 30 s windows.

Results Prepubertal children and well-trained adult endurance athletes showed significantly faster HRR than untrained adults from 30 s post-exercise until the end of recovery ($p < 0.05$). Ln $RMSSD_{30}$ was significantly higher in prepubertal children and athletes than untrained adults over the post-exercise time interval 60–150 s ($p < 0.05$). No significant differences were observed for HRR and Ln $RMSSD_{30}$ between prepubertal children and athletes.

Conclusion Prepubertal children and well-trained adult endurance athletes exhibited comparable and faster HRR and parasympathetic reactivation than untrained adults following maximal exercise. This indirectly suggests that oxidative profile may be preserved by exercise training during growth and maturation to offset the decline in post-exercise HRR, parasympathetic reactivation and aspects of metabolic health.

Keywords Growth · Heart rate variability · Autonomic nervous system · Recovery · Trained athletes

Abbreviations

ANOVA	Analysis of variance
BM	Body mass

HF	High frequency
HR_{max}	Maximal heart rate
HRR	Heart rate recovery
HRV	Heart rate variability
[La]	Blood lactate concentration
MAS	Maximal aerobic speed
PHV	Peak height velocity
RER	Respiratory exchange ratio
RMSSD	Root mean square of successive differences in heart beats
$\dot{V}O_{2\,max}$	Maximal oxygen uptake

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Introduction

Prepubertal children are consistently shown to have a faster heart rate recovery (HRR) following high-intensity exercise than adolescents (Buchheit et al. 2011; Goulopoulou

et al. 2006) and untrained adults (Baraldi et al. 1991; Birat et al. 2018; Guilkey et al. 2014; Hebestreit et al. 1993). The analysis of heart rate variability (HRV) in both time and frequency domains (Buchheit et al. 2011; Guilkey et al. 2014) indicated that the faster HRR in prepubertal children resulted from a greater parasympathetic reactivation of the autonomic nervous system after exercise. For instance, Guilkey et al. (2014) showed that the root mean square of successive differences in heart beats (RMSSD) was greater within 5–10 min after maximal exercise in prepubertal boys than men. Similarly, Buchheit et al. (2011) reported a greater mean RMSSD value within 5–10 min after maximal exercise in less mature (pre-peak height velocity age group) than more mature highly trained young male soccer players (circum- and post-peak height velocity age groups), suggesting that maturational differences in post-exercise parasympathetic reactivation might largely account for the transient HRR decrease from childhood into adolescence. However, this assertion remains to be confirmed since vagal-related HRV indices of autonomic nervous activity have been poorly documented using time-varying analysis, notably in the early stage of recovery in which HRR was found to be clearly faster in prepubertal children (Baraldi et al. 1991; Birat et al. 2018; Guilkey et al. 2014; Hebestreit et al. 1993). In addition, the greater post-exercise parasympathetic reactivation in prepubertal children has not always been reported when considering other vagal-related indices, such as baroreflex sensitivity (Buchheit et al. 2011). This information is of great importance since slower HRR kinetics and lesser parasympathetic reactivation following exercise have been associated with several health outcomes such as heart failure, hypertension, diabetes, and are considered as being reflective from an increased risk of all-cause mortality (Cole et al. 1999).

Beyond age, training background has also been shown to exert a significant influence on inter-individual post-exercise HRR in adults. For instance, Matsuo et al. (2014) showed that high-intensity aerobic interval training improves maximal oxygen uptake ($\dot{V}O_{2\,max}$) and HRR after maximal exercise in sedentary 29-year-old male adults. In addition, while adults with a strong sprint training background predominantly rely on anaerobic energy support during exercise, endurance athletes rely notably on oxidative energy pathways than either untrained adults or sprint-trained athletes (Pesta et al. 2013). This more oxidative profile in endurance athletes translates particularly into (i) a faster HRR following high-intensity exercise than untrained adults (Birat et al. 2018; Dixon et al. 1992; Short and Sedlock 1997) and (ii) a greater parasympathetic reactivation of the autonomic nervous system in the early stage of recovery in endurance athletes than untrained adults (Dixon et al. 1992). In this context, one might suggest that

post-exercise parasympathetic reactivation in prepubertal children could be similar to that observed in well-trained adult endurance athletes following maximal exercise, indirectly suggesting that a more oxidative profile could offset the age-related decline in post-exercise HRR, parasympathetic reactivation and aspects of metabolic health during growth and maturation (Buchheit et al. 2011). However, direct scientific evidence showing such a result has not been specifically sought. The beneficial effects of aerobic training on cardiorespiratory fitness ($\dot{V}O_{2\,max}$), HRR and cardiac autonomic nervous system activity were demonstrated in 10-year-old obese children (Prado et al. 2010); so, the relative concurrent effects of age, maturation and physical fitness in the healthy population remain to be determined.

Therefore, the purpose of the present study was to determine whether, unlike untrained adults, prepubertal children and well-trained adult endurance athletes exhibit a comparable parasympathetic reactivation translating into similar HRR kinetics. We hypothesized that the HRV vagal indices-derived post-exercise parasympathetic reactivation would be similar in prepubertal children and well-trained adult endurance athletes, resulting in comparable HRR kinetics following maximal exercise in both populations. It is also presumed that untrained adults exhibit slower HRR kinetics and lesser parasympathetic reactivation early in the recovery period than prepubertal children and well-trained adult endurance athletes.

Materials and methods

Participants

Twelve healthy boys (8–14 years), 14 untrained men (18–24 years) and 16 well-trained adult male endurance athletes (18–33 years) volunteered to participate in the present study. Due to the potential influence of sexual hormones on parasympathetically-mediated HRV, girls and women were excluded from the experimental protocol to avoid any influence of menstrual cycle phase on HRR (Schmalenberger et al. 2019). To be included, boys and untrained men had to perform recreational physical activity for ≤ 4 h per week and be free of any medical contraindications to physical activity. Boys were prepubertal, based on the assessment of their somatic maturity (see below). None were involved in any vigorous physical activity or engaged in a specific aerobic training program. Boys were recruited from primary and secondary schools while untrained men were university students. Endurance-trained adult athletes were engaged in long-distance physical activities for ≥ 15 h per week for at least 2 years and all had a multi-sport training background before specializing in their current discipline. They were

national-level competitive athletes (i.e., triathletes, long-distance runners). They were recruited from local sports clubs (triathlon, swimming, athletics). This study was approved by an Institutional Ethics Review Board (Protection Committee of People for Biomedical Research, Ile de France IV, n° 2019-A01071-56) and was conducted in conformity with the policy statement regarding the use of human subjects as outlined in the sixth Declaration of Helsinki. All experimental procedures were clearly explained to the participants, who then gave written assent before the commencement of testing. Written consent was also obtained from parents/guardians before boys were accepted in the study.

Experimental procedure (design)

All participants were tested in a single experimental session and abstained from any vigorous physical activity for at least 24 h before the experiment. First, anthropometric characteristics and maturity status were evaluated. After resting supine for 7 min in a quiet place, the participants then performed an incremental running test on an outdoor synthetic track to determine their maximal O_2 uptake ($\dot{V}O_{2\,max}$) and maximal aerobic speed (MAS). Finally, immediately after completion of exercise, the participants laid down during a 5 min recovery period. Gas exchange, heart rate (HR) and HRV were measured before, during and after the incremental running test, while blood lactate concentration was measured before and after the test (see below for further details). The tests were performed on average at 20.3 °C and 53% of relative humidity.

Anthropometric characteristics and maturity status assessment

Body mass (BM) was measured using a digital weight scale (TANITA, BC-545 N, Japan) and standing height was assessed using a portable stadiometer with the participants barefoot (TANITA, HR001, Japan). Sitting height was measured with the stadiometer while the participants sat on the floor with their back against a wall. Body mass index (BMI) was subsequently calculated using the following formula: mass divided by height squared (kg m^{-2}). Maturity offset (MO in years) was determined to assess somatic maturity (i.e., years to (from) age at peak height velocity, APHV) by using chronological age, standing height, sitting height and BM. Its calculation was based on sex-specific regression equations according to the method proposed by Mirwald et al. (2002). Participants were considered as pre-pubertal, pubertal or post-pubertal based on their MO (pre-pubertal: < -1 PHV, pubertal: -1 to $+1$ PHV, post-pubertal: $> +1$ PHV), as previously done (Birat et al. 2020).

Incremental run field test

Each participant performed an incremental run test (Vam-Eval) on a 400 m outdoor athletics track to determine $\dot{V}O_{2\,max}$ and MAS. The Vam-Eval test (Berthoin et al. 1996) was chosen because it allows the assessment of cardio-respiratory fitness and is a common and well-learned activity within the population (Mendez-Villanueva et al. 2010). In addition, this test is commonly used and easier to administer in children (Mendez-Villanueva et al. 2010), and highly reliable for the evaluation of $\dot{V}O_{2\,max}$ (Leger and Boucher 1980). The incremental running test began at an initial speed of 8 km h^{-1} and increased 0.5 km h^{-1} every minute until the participant stopped due to volitional exhaustion. During the test, the participants adjusted their running speed as a function of the auditory signal timed to match 20 m intervals marked by cones around the 400 m outdoor athletics track. The test ended when participants failed to reach the next cone in the required time. During the test, participants were verbally encouraged by the experimenters. The last completed stage was recorded as the MAS of participant (km h^{-1}). Oxygen uptake ($\dot{V}O_{2\,max}$), carbon dioxide output ($\dot{V}CO_2$), minute ventilation and heart rate (HR) were continuously recorded before, during and after the incremental running test (details below). The respiratory exchange ratio (RER) was subsequently computed as the ratio of $\dot{V}CO_2$ to $\dot{V}O_2$, and $\dot{V}O_{2max}$ was determined over the last 30 s of the test, and considered to be reached when at least two of the following criteria were met: (i) maximal respiratory exchange ratio (RER$_{max}$) ≥ 1.1, (ii) maximal HR (HR$_{max}$) $\geq 95\%$ of the age-predicted HR$_{max}$ (208.6–0.7 age) (age in years) (Shargal et al. 2015), and (iii) blood lactate concentration higher than 6 and 8 mmol L^{-1} in boys and men, respectively (Armstrong and Welsman 1994).

Data acquisition and processing

HRR and HRV analysis

During the testing session, R–R intervals were continuously monitored using a Polar recorder (Polar H7 V800 Z0, Kempele, Finland), previously validated by Giles et al. (2016). Resting HR (HR$_{rest}$) values obtained from the R–R interval were determined in a supine position before the Vam-Eval test, and maximal HR (HR$_{max}$) was obtained over the last 30 s of the test. As HR$_{rest}$ and HR$_{max}$ differed between groups, the post-exercise HRR kinetics were determined by considering the net changes (HR$_{rest}$ subtracted from HR measured) expressed as percentage of HR$_{max}$ in 30 s intervals during the 5 min post-exercise recovery period.

HRV was analyzed off-line in the time domain to assess post-exercise parasympathetic reactivation by means of

R–R intervals recorded during the recovery period using the Kubios standard software version 3.1.0 (Varsitie 22, 70,150 Kuopio, FINLAND). R–R intervals were edited and visually inspected so that ectopic beats could be replaced by interpolated data from adjacent normal-to-normal (NN) intervals (Dupuy et al. 2012). Parasympathetic reactivation was quantified in the time domain using the natural logarithm of the root mean square of successive deviations of the R–R interval (Ln RMSSD) (Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996). Ln RMSSD were calculated for each 30 s segment in recovery, i.e. Ln $RMSSD_{30}$, as done previously (Goldberger et al. 2006) and recently recommended by Kim et al. (2021). The power spectrum of HRV was not investigated due to inconsistencies in high frequency power (HF) compared to RMSSD, notably in the early phase of post-exercise recovery (Baek et al. 2015; Hung et al. 2020). Furthermore, Kim et al. (2021) have recently shown that segments of at least 120 s were required to correctly quantify HF immediately after exercise completion, hence ruling out the possibility of obtaining segments of sufficient duration during the 5 min post-exercise recording in the present study. The relevance of analyzing RMSSD rather than HF immediately after exercise completion is also related to excellent agreement and accuracy of HRV in time domain analyses (Baek et al. 2015; Hung et al. 2020). Indeed, time domain indices were found not to be as influenced by the different breathing patterns as frequency domains are, which would result in higher reliability for time domain indices during the post-exercise recovery period of non-static exercises (Al Haddad et al. 2011; Billman 2013; Penttila et al. 2001).

Gas exchange and ventilation recordings

Oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$) and minute ventilation were recorded breath-by-breath throughout the experimental procedure using a mobile spiroergometry system (METAMAXR® 3B, CORTEX Biophysik GmbH, Leipzig, Germany).

Blood sampling and analysis

Arterialized capillary blood samples (20 μL) were taken from the fingertip at rest ($[La]_{rest}$) and 1, 3 and 5 min post-exercise to measure the time course of blood lactate concentration changes. $[La]_{peak}$ was determined as the highest value over the post-exercise recovery period. Blood lactate concentrations were determined using the Lactate Scout$^+$ analyzer (EKF Diagnostic, Leipzig, Germany). The device was systematically calibrated before each experimental session.

Statistical analysis

Data were screened for normality of distribution and homogeneity of variances using a Shapiro–Wilk normality test and the Bartlett's test, respectively. If the samples were not normally distributed, data were log-transformed using a natural logarithm (Ln). One-way (group) ANOVA was used to compare age, anthropometric characteristics (BM, height, BMI), physiological parameters obtained at rest (HR_{rest}, % age-predicted HR_{max}, $[La]_{rest}$) and at completion of the test ($\dot{V}O_{2max}$, MAS, HR_{max}, $[La]_{peak}$). When ANOVA revealed a significant effect, LSD Fisher post-hoc test was applied to test discrimination between means. Furthermore, two-way (group × time) ANOVA with repeated measures was used to analyze the time course of HR, Ln RMSSD and [La] during the post-exercise recovery period. When ANOVA revealed a significant main or interaction effect, LSD Fisher post-hoc test was applied to test the discrimination between means. The effect size was assessed using the partial eta-squared (η^2) and ranked as follows: ~0.01 = small effect, ~0.06 = moderate effect, ≥ 0.14 = large effect (Cohen 1969). The limit for statistical significance was set at $p < 0.05$. Statistical procedures were performed using Statistica 8.0 software (Statsoft, Inc., USA). Results are presented as means ± standard deviation (SD) excepted for Ln RMSSD, which is illustrated in figure as means ± standard error of the mean (SEM) to allow better clarity.

Results

Participants' physical characteristics

The physical characteristics of participants are presented in Table 1.

ANOVA revealed significant differences between groups for age ($F_{(2,39)} = 48.5$, $p < 0.001$, $\eta^2 = 0.71$, power = 1.0), height ($F_{(2,39)} = 27.9$, $p < 0.001$, $\eta^2 = 0.59$, power = 0.99), BM ($F_{(2,39)} = 25.8$, $p < 0.001$, $\eta^2 = 0.57$, power = 0.99) and BMI ($F_{(2,39)} = 14.2$, $p < 0.001$, $\eta^2 = 0.42$, power = 0.99). Post-hoc tests showed no significant difference in height or BM between untrained adults and well-trained adult endurance athletes. However, untrained adults were on average younger and showed significantly higher BMI values than well-trained adult endurance athletes ($p < 0.05$ for both). Finally, age, height, BM and BMI were significantly lower in children than untrained adults and well-trained adult endurance athletes ($p < 0.001$ for all).

Table 1 Participants' physical characteristics

	C $n=12$	EA $n=16$	UA $n=14$
Age (year)	12.3 ± 1.6	24.5 ± 4.8***	21.8 ± 2.2***,[a]
Years to (from) APHV	-2.3 ± 1.2	–	–
APHV (year)	14.5 ± 0.6	–	–
Height (cm)	154.3 ± 11.2	175.1 ± 7.0***	176.7 ± 7.2***
BM (kg)	43.5 ± 9.9	65.5 ± 8.6***	71.6 ± 12.5***
BMI (kg m^{-2})	18.0 ± 2.0	21.1 ± 2.0***	22.8 ± 2.8***,[a]

Values are means $\pm$ SD

C children, *EA* well-trained adult endurance athletes, *UA* untrained adults, *APHV* age at the peak height velocity, *BM* body mass, *BMI* body mass index

[a]Significantly different from well-trained adult endurance athletes, $p < 0.05$

***Significantly different from children, $p < 0.001$

Incremental run field test

Before the test

ANOVA revealed a significant group effect for HR$_{rest}$ (F$_{(2, 39)}$ = 12.2, $p < 0.001$, $\eta^2 = 0.39$, power = 0.99). HR$_{rest}$ was higher on average in untrained adults than well-trained adult endurance athletes but this difference did not reach statistical significance (see Table 2). Also, children displayed significantly higher HR$_{rest}$ values than untrained adults and well-trained adult endurance athletes ($p < 0.01$

and $p < 0.001$, respectively). Finally, ANOVA revealed no significant group effect for [La]$_{rest}$.

At completion of the maximal test

Performance and physiological outcomes obtained at completion of the Vam-Eval test are displayed in Table 2. ANOVA revealed significant differences between groups for absolute $\dot{V}O_{2max}$ (F$_{(2,39)}$ = 70.9, $p < 0.001$, $\eta^2 = 0.77$, power = 1.0), $\dot{V}O_{2max}$ relative to BM (F$_{(2,39)}$ = 54.9, $p < 0.001$, $\eta^2 = 0.74$, power = 1.0), MAS (F$_{(2,39)}$ = 81.9, $p < 0.001$, $\eta^2 = 0.81$, power = 1.0), HR$_{max}$ (F$_{(2,39)}$ = 3.4, $p < 0.05$, $\eta^2 = 0.15$, power = 0.6) and [La]$_{peak}$ (F$_{(2,39)}$ = 5.3, $p < 0.01$, $\eta^2 = 0.21$, power = 0.8). As expected, well-trained adult endurance athletes displayed significantly higher $\dot{V}O_{2max}$ and MAS values than untrained adults and children ($p < 0.001$ for all). Additionally, [La]$_{peak}$ was similar in well-trained adult endurance athletes and untrained adults but higher in both adult groups than children ($p < 0.05$ at least). However, $\dot{V}O_{2max}$ relative to BM was not significantly different between children and untrained adults. Finally, ANOVA showed no significant group effect for percentage-predicted HR$_{max}$ or RER.

Post-exercise HRR

Data describing HRR kinetics following the Vam-Eval test are displayed in Fig. 1. ANOVA revealed a significant group × time interaction effect throughout the post-exercise recovery period (F$_{(39,390)}$ = 3.4, $p < 0.001$, $\eta^2 = 0.15$, power = 1.0). Post-hoc tests revealed a faster HRR in

Table 2 Physiological variables measured at rest and after completion of maximal exercise

	C $n=12$	EA $n=16$	UA $n=14$
Resting conditions			
HR$_{rest}$ (bpm)	86.9 ± 12.0	66.8 ± 10.2***	73.7 ± 10.1**
[La]$_{rest}$ (mmol L^{-1})	2.0 ± 0.9	2.0 ± 1.2	1.7 ± 0.5
After maximal exercise			
$\dot{V}O_{2max}$ (L min^{-1})	2.2 ± 0.5	4.4 ± 0.6***	3.5 ± 0.4***,[a]
$\dot{V}O_{2max}$ (mL min^{-1} kg^{-1}BM)	51.6 ± 7.5	67.3 ± 4.4***	48.4 ± 3.7[a]
MAS (km h^{-1})	13.0 ± 1.5	18.9 ± 1.2***	14.6 ± 1.1**,[a]
HR$_{max}$ (bpm)	205.7 ± 7.4	196.4 ± 10.5*	199.1 ± 9.8
% age-predicted HR$_{max}$	102.9 ± 3.8	102.8 ± 5.1	103.2 ± 5.1
RER	1.19 ± 0.05	1.20 ± 0.09	1.20 ± 0.10
[La]$_{peak}$ (mmol L^{-1})	7.6 ± 2.9	11.0 ± 2.5*	11.5 ± 5.2**

Values are means $\pm$ SD

C children, *UA* untrained adults, *EA* well-trained adult endurance athletes, *HR$_{rest}$* resting heart rate, *[La]$_{rest}$* resting blood lactate concentration, *$\dot{V}O_{2max}$* maximum oxygen uptake, *BM* body mass, *MAS* maximal aerobic speed, *HR$_{max}$* maximum heart rate, *RER* respiratory exchange ratio, *[La]$_{peak}$* peak blood lactate concentration

[a]Significantly different from well-trained adult endurance athletes, $p < 0.001$

*,**,*** Significantly different from children, $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively
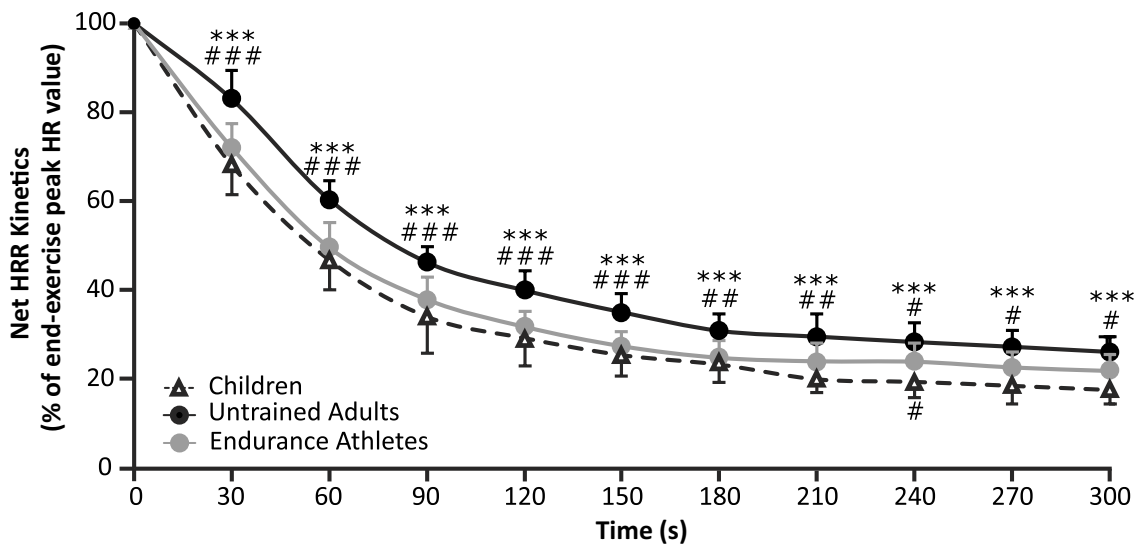
Fig. 1 Net heart rate recovery (HRR) kinetics measured after the Vam-Eval test in children, untrained adults and well-trained adult endurance athletes. Values are expressed as a percentage of end-exercise peak heart rate. * Significantly different from children; # significantly different from well-trained adult endurance athletes. One item $p < 0.05$, two items $p < 0.01$, and three items $p < 0.001$

children and well-trained adult endurance athletes than untrained adults from 30-s post-exercise until the end of recovery ($p < 0.05$ at least). However, HRR was not significantly different between children and well-trained adult endurance athletes except at 240 s post-exercise ($p < 0.05$).

Post-exercise HRV

Ln $RMSSD_{30}$ values during the post-exercise recovery period are presented in Fig. 2. ANOVA revealed a significant group × time interaction effect for Ln $RMSSD_{30}$ ($F_{(39,351)} = 1.9$, $p < 0.05$, $\eta^2 = 0.09$, power $= 0.97$). Compared to end-exercise, Ln $RMSSD_{30}$ significantly increased in
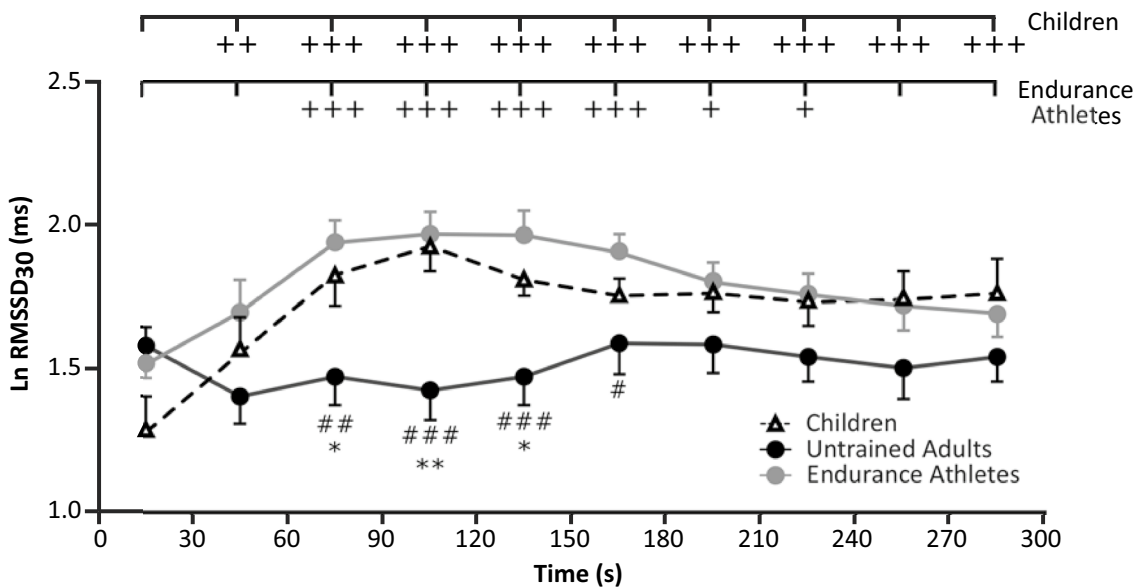
Fig. 2 Time course of the natural logarithm of the root mean square of successive differences in R–R intervals measured over consecutive 30 s windows (Ln $rMSSD_{30}$) during the 5 min post-exercise recovery period in children, untrained adults and well-trained adult endur-

ance athletes. * Significantly different from children; # significantly different from well-trained adult endurance athletes; + significantly different from the end-exercise value. One item $p < 0.05$, two items $p < 0.01$, and three items $p < 0.001$

children from the 30–60 s interval until the end of recovery period, and from the 60–90 s interval until the 210–240 s interval in well-trained adult endurance athletes ($p < 0.05$ at least). On the contrary, no significant change was observed at any time point in untrained adults throughout the recovery period. Post-hoc tests showed significantly greater Ln $RMSSD_{30}$ values in children and well-trained adult endurance athletes than untrained adults in the 60–150 s time interval ($p < 0.05$ at least). In addition, no significant differences in Ln $RMSSD_{30}$ values were observed between children and well-trained adult endurance athletes.

Blood lactate concentration

The time course of blood lactate concentration is displayed in Fig. 3. ANOVA revealed no significant group × time interaction effect. However, there were significant group ($F_{(2,39)} = 5.7$, $p < 0.01$, $\eta^2 = 0.23$, power = 0.84) and time ($F_{(2,39)} = 17.7$, $p < 0.001$, $\eta^2 = 0.31$, power = 0.99) effects. Post-hoc tests showed significantly lower blood lactate concentrations in children than untrained adults and well-trained adult endurance athletes when all lactate concentrations were pooled ($p < 0.01$). However, no significant difference in blood lactate concentrations were observed between untrained adults and well-trained adult endurance athletes when all values were considered.

Discussion

The aim of the present study was to determine whether, contrary to untrained adults, prepubertal children exhibit a post-exercise parasympathetic reactivation profile comparable to well-trained adult endurance athletes and whether this results in similar HRR kinetics in the two populations. The main results confirm our hypotheses since prepubertal children and well-trained adult endurance athletes showed comparable and faster HRR kinetics than untrained adults after maximal running exercise. These results were associated with a greater and earlier parasympathetic reactivation in prepubertal children and well-trained adult endurance athletes than untrained adults from the onset of recovery period, as evidenced by the greater Ln $RMSSD_{30}$ values in prepubertal boys and well-trained adult male endurance athletes. Our findings indirectly suggest that oxidative profile may be preserved during growth and maturation to offset the decline in post-exercise HRR and parasympathetic reactivation over this period, therefore, minimizing the risk of developing chronic diseases such as heart failure, diabetes or hypertension throughout the lifespan.

The results of the present study are consistent with previously published data showing a faster HRR and greater parasympathetic reactivation of the autonomic nervous system after exercise in prepubertal children than untrained adults (Baraldi et al. 1991; Birat et al. 2018; Guilkey et al. 2014; Hebestreit et al. 1993). They also confirm that the more oxidative profile in endurance athletes translates into (i) a faster HRR following exercise than untrained adults (Birat et al. 2018; Dixon et al. 1992; Short and Sedlock 1997), and (ii) a greater post-exercise parasympathetic reactivation of the autonomic nervous system, than untrained adults (Dixon et al. 1992). However, our data also show for the first time that the faster HRR kinetics in prepubertal children is associated with greater Ln $RMSSD_{30}$ in the early stage of recovery, contrary to previous studies that instead analyzed and averaged HRV variables within 5–10 min after exercise cessation (Goulopoulou et al. 2006; Guilkey et al. 2014). Another original finding is that prepubertal children displayed a HRR similar to that of well-trained adult endurance athletes, and this similitude was associated with a comparable parasympathetic reactivation between both populations. Indeed, while Ln $RMSSD_{30}$ concomitantly and significantly increased in the early stage of recovery in both prepubertal children and well-trained adult endurance athletes, it remained unchanged

Fig. 3 Time course of blood lactate concentration following the Vam-Eval test in children, untrained adults and well-trained adult endurance athletes. Measurements were done at rest and 1, 3 and 5 min after completion of the Vam-Eval test
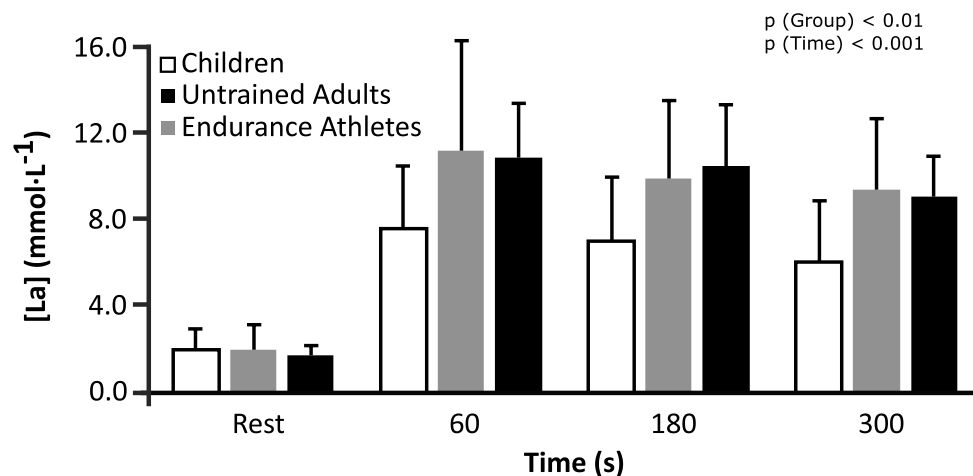
in untrained adults (Fig. 2). Collectively, the present findings add to the existing literature that the faster parasympathetic reactivation encountered in prepubertal children than untrained adults is similar to that reported in well-trained endurance adult athletes, possibly accounting for the faster post-exercise HRR in these two populations. These results were apparent despite normalized $\dot{V}O_{2max}$ values being lower in prepubertal children (51.6 mL min^{-1} kg^{-1}BM) than endurance athletes (67.3 mL min^{-1} kg^{-1}BM), and so cannot be immediately attributed to aerobic capacity alone.

A potential mechanism underpinning the between-group differences in post-exercise HRR could be the accumulation of chemical mediators of the chemoreflex control of heart rate, such as blood norepinephrine, H$^+$ ions or lactate (Buchheit et al. 2007). Specifically, the persistent, important concentration of these exercise-induced chemical mediators might stimulate the post-exercise metaboreflex, preserving sympathetic nervous activity during recovery (Gujic et al. 2007). This could then translate into a reduced or delayed post-exercise parasympathetic reactivation in individuals with higher post-exercise blood lactate or H$^+$ ion concentrations (Buchheit et al. 2007). However, this assumption remains to be confirmed since in the present study a lesser blood lactate accumulation was observed in prepubertal children than in well-trained adult endurance athletes (Fig. 3) while no significant difference was observed regarding post-exercise Ln RMSSD$_{30}$ between both populations (Fig. 2). In addition, Ln RMSSD$_{30}$ was found to be higher in well-trained adult endurance athletes than untrained adults despite similar post-exercise peak blood lactate concentrations between both populations. Therefore, despite the conclusions previously drawn by some authors (Buchheit et al. 2007,2011), the results of the present study suggest that blood lactate concentration may not be a primary discriminatory factor accounting for the between-group differences in HRR and HRV.

Among other potential mechanisms, baroreflex sensitivity could account for the between-group differences in HRR and vagal-related HRV since it may be dependent upon an individual's endurance training background and oxidative profile. Indeed, endurance training has been shown to change the neural component of the baroreflex arc (Komine et al. 2009), enhancing its sensitivity, which could consequently promote post-exercise parasympathetic reactivation. In addition, baroreflex sensitivity was found to be greater in endurance-trained athletes than nonathletes in adolescent (Subramanian et al. 2019) and adult (Shin et al. 1995) populations, and also greater in prepubertal children who depended more on oxidative than anaerobic metabolism during exercise than their untrained adult counterparts (Chirico et al. 2015; Ratel and Blazevich 2017). Therefore, even if baroreflex sensitivity was not measured in the present study, the greater post-exercise vagal reactivation in well-trained adult endurance athletes and prepubertal children than untrained adults might suggest a greater baroreflex-mediated cardiac parasympathetic modulation in these two populations.

Strengths and limitations

Several limitations of the present study should be mentioned. First, the novelty of the incremental run field test could have influenced the HRR and HRV outcomes, especially in prepubertal children and untrained adults who were not habituated to use maximal intensities during daily activity. Nevertheless, at exercise completion, all participants achieved the criteria for attaining $\dot{V}O_{2max}$ and indicating their maximal effort (see Table 2). Second, the aerobic fitness of the boys tested should be also considered as similar results to the athletes might be expected if their aerobic fitness was similar. However, $\dot{V}O_{2max}$ values of prepubertal boys were comparable to those of moderately active boys not participating in formal training or organized sports (Turley and Wilmore 1997), hence ruling out any potential effect of endurance training or daily physical activity on post-exercise HRR and parasympathetic reactivation in the boys. While $\dot{V}O_{2max}$ values of the boys might be considered relatively high (51.6 ± 7.5 mL min^{-1} kg^{-1}BM), it should be remembered that these values were obtained in a running-based tests, and values obtained during running are typically 7–15% higher than those obtained in cycle ergometry, probably the greater active muscle mass increases oxygen demand (Falk and Dotan 2019). Finally, the analysis of post-exercise parasympathetic reactivation in the supine position could be also scrutinized, but this position has previously shown a good reproducibility for temporal indices of HRV in healthy men (da Cruz et al. 2019). However, it remains to be determined whether our data are also consistent with those measured in other body positions since parasympathetic reactivation was found to be faster following exercise in supine position than seated or upright positions (Buchheit et al. 2009).

A unique strength of the present study is that parasympathetic reactivation was compared between prepubertal children, untrained adults and endurance adult athletes over consecutive 30 s windows in the early stage of recovery, contrary to previous studies which rather analyzed and averaged HRV variables within 5–10 min after exercise cessation (Goulopoulou et al. 2006; Guilkey et al. 2014). In addition, temporal changes in HRR and HRV were rapidly monitored since participants were asked to lay down immediately after completion of the running exercise. Indeed, the time delay between the end of exercise and achievements of the required position was less than 5 s. Thus, stationarity of the data was optimized from the onset of recovery, contrary to previous studies in which HRV was measured later in the post-exercise recovery period (Buchheit et al. 2007; Dixon et al. 1992; Goulopoulou et al. 2006; Guilkey et al. 2014).

Conclusion

The present results demonstrate comparable and faster HRR kinetics in prepubertal children and well-trained adult endurance athletes than untrained adults after maximal exercise. This result was associated with a greater and earlier parasympathetic reactivation in the children and adult endurance athletes. Remarkably, no differences in HRR and Ln RMSSD$_{30}$ were observed between children and adult endurance athletes. Thus, the present data provide additional evidence that prepubertal children are metabolically comparable to well-trained adult endurance athletes (Birat et al. 2018; Bontemps et al. 2019; Ratel and Blazevich 2017). Thus, the mechanisms underpinning the faster HRR in these two populations could be considered as innate in prepubertal children and acquired in endurance athletes. Finally, the results indirectly suggest that interventions should be imposed to preserve oxidative profile through childhood and adolescence, to offset the decline in HRR and parasympathetic reactivation in the transition to adulthood.

Translational perspective

Our data provide strong indications as to how growth and maturation may alter post-exercise HRR and parasympathetic reactivation, and how a more oxidative profile could offset this decline during growth and maturation. In a clinical context, the understanding of child–adult differences in post-exercise HRR kinetics and parasympathetic reactivation may prove central to the development of aerobic exercise-based strategies for the prevention and treatment of many metabolic diseases related to mitochondrial oxidative dysfunction (e.g., in obese, insulin-resistant, hypertensive and diabetic patients), which are often accompanied by aerobic deconditioning during adolescence and adulthood (Eisenmann 2007), but have a very low prevalence in preadolescent children (Moran et al. 1999). This is of great importance, since the level of physical activity and aerobic fitness in children has decreased over the last two decades, and especially during the Covid-19-related-lockdowns (Ammar et al. 2020; Cachon-Zagalaz et al. 2021). In occupational, exercise and sporting contexts, endurance-based training programs, including either continuous exercise at moderate intensity or high-intensity intermittent exercise, could be proposed to offset the decline in post-exercise HRR and parasympathetic reactivation during growth, maturation (Buchheit et al. 2011) and aging (Cornelissen et al. 2010), but also to optimize recovery and endurance training adaptations in young as well as masters athletes (Borges et al. 2017).

New and noteworthy

- Prepubertal children exhibited a post-exercise parasympathetic reactivation comparable to well-trained adult endurance athletes, but not untrained adults, resulting in similar HRR kinetics in both populations.
- The results indirectly suggest that oxidative profile should be preserved by exercise training during growth and maturation to offset the decline in post-exercise HRR and parasympathetic reactivation over this period, favorably impacting the risk of chronic diseases such as heart failure, diabetes or hypertension.

Declarations

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