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ORIGINAL ARTICLE

Concomitant application of sprint and high-intensity interval training on maximal oxygen uptake and work output in well-trained cyclists

Paulina Hebisz[1] · **Rafał Hebisz**[1,2] · **Marek Zatoń**[1] · **Bartosz Ochmann**[1] · **Natalia Mielnik**[1]

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Abstract
Purpose In this study, we compared the effects of two different training modalities on maximal oxygen uptake and work output.
Methods Participants included 26 well-trained mountain bike cyclists were divided into two groups. The first group trained using a conventional endurance protocol at steady-state (moderate) intensity and variable-intensity (high-moderate-low) free of maximal efforts. The second group combined endurance training with a sprint and high-intensity interval training protocol, which, respectively, were based on 30 s maximal repetitions and 4 min high intensity repetitions. Training duration was 8 weeks. A graded exercise test was administered pre- and post-training. Work output, oxygen uptake, minute pulmonary ventilation, heart rate and stroke volume were determined during the test.
Results While work output significantly increased post-training in both groups ($P < 0.05$), the interval training group showed a greater magnitude of change (from 284.4 ± 91.9 to 314.2 ± 95.1 kJ) than the endurance training group (from 271.8 ± 73.3 to 283.4 ± 72.3 kJ). Significant increases in maximal oxygen uptake (from 57.9 ± 6.8 to 66.6 ± 5.3 ml kg^{-1} min^{-1}), maximal pulmonary ventilation and stroke volume were observed only in the interval training group.
Conclusions An exercise protocol involving endurance and sprint and high-intensity interval training was found to induce positive effects on maximal oxygen uptake in a group of well-trained cyclists with several years athletic experience.

Keywords Interval training · Maximal oxygen uptake · Cycling

Abbreviations

ANOVA	Analysis of variance
E	Endurance training group
H^+	Hydrogen ion
HIIT	High-intensity interval training
HRmax	Maximal heart rate
I	Interval and endurance training group
MTB	Mountain bike
SV	Stroke volume
VE	Minute pulmonary ventilation
VO_2	Oxygen uptake
VO_2max	Maximal oxygen uptake

Introduction

Maximal oxygen uptake (VO_2max) is a global indicator of fitness performance (Bassett and Howley 2000). It reflects cardiorespiratory effectiveness in supplying oxygen to working muscle as well as the ability of the muscular system to utilise oxygen during exercise. VO_2max is contingent on numerous supply- and demand-side determinants including minute pulmonary ventilation, pulmonary diffusion capacity, cardiac output, haemoglobin level, capillary density, mitochondrial volume density and oxidative enzyme activities (Bassett and Howley 2000; Warburton

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✉ Paulina Hebisz
paulinahebisz@interia.pl

[1] Department of Physiology and Biochemistry, University School of Physical Education in Wroclaw, 35 J.I. Paderewski Avenue, 51-612 Wroclaw, Poland

[2] National Team Coach, Polish Cycling Federation, Pruszków, Poland

Table 1 Anthropometric and physiological characteristics of groups I and E

Group	Age (years)	Height (cm)	Mass (kg)	VO_2max (ml kg^{-1} min^{-1})	W (kJ)
I	24.4 ± 3.7	178.4 ± 7.2	66.8 ± 8.7	57.9 ± 6.8	284.4 ± 91.9
E	25.1 ± 5.1	175.8 ± 4.3	63.9 ± 6.1	61.3 ± 7.5	271.8 ± 73.3

Data are presented as mean ± standard deviation

VO_2max maximal oxygen uptake during the graded exercise test, *W* work output during the graded exercise test

and Gledhill 2006). According to Wagner (2006), the most important factor in the development of VO_2max is cardiac output and locomotor muscle blood flow. Nonetheless, all of the above factors are interrelated, if one of the mechanisms are modified the entire oxygen transport and extraction chain is subject to change (Wagner 2006, 2011; Warburton and Gledhill 2006).

The results of numerous studies make it abundantly clear that elite performance in endurance sports requires high VO_2max capabilities (Le Meur et al. 2009; Lucia et al. 2001; Martino et al. 2002; Padilla et al. 1999). The higher the oxygen consumption, the more energy can be produced and translated into power or speed (Padilla et al. 1999). However, there are physiological limitations to individual VO_2max. Lucia et al. (2010) stated that variability in VO_2max is influenced to a large degree by genetics. In contrast, Bouchard et al. (2011) attribute the influence of genetics only in individuals prior to an appropriate training intervention. Astrand and Saltin (1967) stated that VO_2max may significantly increase (by 50 %) after exposure to adequate and regular exercise.

It is believed that continuous endurance training is effective in enhancing VO_2max, as prolonged exercise is dominated by aerobic energy metabolism (Gledhill et al. 1994; Warburton et al. 2004). This form of training is known to increase both cardiac output and stroke volume, two determinants considered crucial to improving oxygen transport to exercising muscles (Arbab-Zadeh et al. 2004; Gledhill et al. 1994; Goodman et al. 2005). However, there has been an increased focus on other training modalities and their effect on VO_2max in recent years, with a large body of work concentrating on high-intensity interval training (HIIT) (Sloth et al. 2013). Currently, there is consensus that interval training and endurance training as separate modalities are effective in improving VO_2max as they induce increased enzymatic activity, mitochondrial volume density (Burgomaster et al. 2008; Holloszy and Coyle 1984; Pilegaard et al. 2003; Russell et al. 2003) and capillary density (Fluck and Hoppeler 2003; Roxburgh et al. 2014).

Though many studies have documented the impact of interval training on VO_2max, almost all involve examining the effects of a single type of interval training on a sample of sedentary or recreational athletes (Sloth et al. 2013). There is a paucity of data on the influence of a training program linking different interval training variations on VO_2max in athletes with several years professional experience. For this reason, the aim of this work was to compare the effects of two training modalities on VO_2max in well-trained mountain bike (MTB) cyclists. The first intervention would involve conventional endurance training at steady-state (moderate) intensity and variable intensity (high-moderate-low) free of maximal efforts. The second, besides an endurance training component, would involve two interval training protocols: (a) sprint interval training involving several sets of four 30 s maximal cycling efforts interspersed with 90 s rest periods and (b) high-intensity interval training consisting of several 4 min cycling efforts at 90–100 % maximal aerobic power followed by 12 min of moderate-intensity cycling. We hypothesised that both intervention programs would lead to improvements in VO_2max, but that the group of cyclists performing interval training would show a greater magnitude of change primarily by improvements in pulmonary ventilation and stroke volume as a result of the two additional training stimuli.

Methods

Participants

For the purposes of the study, we recruited 26 MTB cyclists of whom the majority were members of the National Team. All participants had at least 5 years of athletic experience and competed in the same cross-country categories (Elite and U23). The study design was approved by the Ethics Committee of the University School of Physical Education in Wroclaw, Poland and carried out in accordance with the Declaration of Helsinki. All of the cyclists provided written consent to participate in the study after being informed about the methods and procedures.

The participants were randomly divided into two groups. Group I completed an interval/endurance training protocol ($n = 13$; nine men and four women) whereas group E realised an endurance training protocol ($n = 13$; ten men and three women). No significant intergroup differences were observed for body height, mass or physical fitness level (determined using a graded exercise test, explained later). These characteristics are presented in Table 1. The groups also did not differ in terms of training status and load, were previous training history primarily involved endurance-based cycling at steady-state (moderate) intensity and variable intensity (high-moderate-low). None of the cyclists had experience with maximal effort exercise characteristic of interval training, only high intensity efforts such as several-minute uphill climbs. All participants followed a similar training plan, in which they trained for 10 months each year from December to the following September. During a typical week training duration was 11–13 h in which a distance of 270–400 km was cycled. During the racing season (from April to September) all of the cyclists participated in 20–25 races. The present intervention encompassed the two last months of the preparatory season which lasts from December to March.

Experimental design

For group I, the training program lasted 8 weeks and involved three cycling protocols. Only one training protocol was performed per daily training session. The program began with protocol (a) on the first day, (b) on the second and (c) on the third day. The fourth day was a day of rest and on the fifth the participants began training with (a) again. They were:

a. Sprint interval training, which was composed of several sets of maximal intensity cycling. Each set consisted of four maximal bouts of 30 s interspersed with 90 s rest periods (similar in design to the Wingate test) and was separated by 20–40 min active recovery at moderate intensity (60–70 % maximal heart rate). The number of sets performed by each participant was determined individually. Sets were repeated until work done decreased by 5 % compared with the highest value recorded during the training session. This criterion resulted in participants completing between two and five sets. Similarly, the duration of active recovery between sets was also tailored to each participant by calculating the time needed to return to acid–base homeostasis via blood hydrogen ion (H^+) concentration (measured after a warm-up and was approximately 44 nmol l^{-1}). This was performed using a RAPIDLab 348 blood gas system (Siemens Healthcare, Germany) and found to require 20–40 min of active recovery.
b. High-intensity interval training, consisting of 4 min of high-intensity cycling (90–100 % maximal aerobic power) followed by 12 min of medium-intensity cycling (60–70 % maximal heart rate). The number of times the 4-min of high-intensity cycling was repeated was also determined individually; the session was ended when work output decreased by 5 % compared with the highest recorded value. This criterion resulted in participants completing between four and seven such repetitions.
c. Endurance training, which was performed at 80–90 % power at the ventilatory threshold for 2–3 h.

For group E, the training program lasted 8 weeks and involved three cycling protocols. Similar to group I, each protocol was performed once a day, beginning with (a) on the first day, (b) on the second day and (b) again on the third day. The fourth day was a day of rest to return to training (a) on the fifth day. These two training modalities were:

a. Variable-intensity endurance training that alternated between 10–15 min of high-intensity cycling (100–110 % power at the ventilatory threshold) and 10–15 min of low- and moderate-intensity effort (50–70 % maximal heart rate) for a total of 2–3 h.
b. Endurance training performed at 80–90 % power at the ventilatory threshold for 2–3 h.

The training load parameters of maximal heart rate (HRmax), power at the ventilatory threshold and maximal aerobic power were determined a priori using a graded exercise test outlined in further detail below. Exercise intensity was continually measured throughout each training session using a RS800CX heart rate monitor (Polar Electro, Finland) and cycling power meter system (PowerTap, United States).

Exercise test

A graded exercise test was administered before and after the 8-week training program in controlled laboratory conditions at the Exercise Laboratory at the University School of Physical Education (PN-EN ISO 9001:2001 certified). The test was performed on a Cyclus two cycle ergometer (RBM Elektronik, Germany). Starting workload was 50 W and increased every 3 min by 50 W until volitional exhaustion. The ergometer was connected to a computer that recorded instantaneous power and time. If a participant was unable to complete an entire 3 min stage 0.28 W per second missed was subtracted from the work rate at that stage. The highest power output determined in the graded exercise test was taken to be the measure of maximal aerobic power. Work done was calculated for each stage in the graded exercise test by multiplying power (e.g., 50 W) by time (180 s). The results were summed across all the completed stages and converted into kilojoules (kJ).

Respiratory function was measured 3 min prior and continued 5 min after the test. The cyclist wore a mask connected to a Quark gas analyser (Cosmed, Italy). The gas analyser was calibrated before use with a reference gas mixture of carbon dioxide (CO_2)—5 %, oxygen (O_2)—16 %, and nitrogen

Table 2 Total work output and cardiorespiratory variables pre- and post-training of groups I and E

	Group I		Group E	
	Pre	Post	Pre	Post
W_{tot} (kJ)	284.4 ± 91.9	314.2 ± 95.1*	271.8 ± 73.3	283.4 ± 72.3*
VO_2max (l min^{-1})	3.9 ± 0.8	4.5 ± 0.7*	3.9 ± 0.6	4.0 ± 0.5
VO_2max (ml kg^{-1} min^{-1})	57.9 ± 6.8	66.6 ± 5.3*	61.3 ± 7.5	62.4 ± 6.9
VEmax (l min^{-1})	160.2 ± 38.4	174.1 ± 36.7*	141.1 ± 24.9	141.6 ± 24.8**
HRmax (beats min^{-1})	189.9 ± 8.0	190.2 ± 8.1	190.5 ± 6.2	191.0 ± 7.1
SV_1 (ml)	115.1 ± 11.6	133.1 ± 18.8*	121.6 ± 8.9	116.7 ± 14.0**
SV_2 (ml)	129.9 ± 26.3	148.9 ± 23.5*	129.6 ± 21.8	131.9 ± 24.0

Data are presented as mean ± standard deviation

W_{tot} total work output during the graded exercise test, VO_2max maximal oxygen uptake during the graded exercise test; *VEmax* maximal pulmonary ventilation, *HRmax* maximal heart rate, SV_1 stroke volume, estimated on the basis of blood pressure measured after graded exercise test, SV_2 stroke volume, estimated on the basis of oxygen uptake and heart rate measured during graded exercise test

* $P < 0.05$ significant difference between before vs. after training program

** $P < 0.05$ significant difference between I vs. E

(N_2)—79 %. Tidal air was analyzed on a breath-by-breath basis to determine oxygen uptake (VO_2), maximal oxygen uptake (VO_2max), carbon dioxide excretion (VCO_2) and minute pulmonary ventilation (VE). Absolute and relative (per kg of body mass) VO_2max was calculated based on the composition of expired air and minute ventilation. The measures were averaged over 30-s intervals. The ventilatory threshold was determined by V-slope analysis of VO_2 and VCO_2 as outlined by Beaver et al. (1986). This method assumes an increase VCO_2 in relation to VO_2 during graded intensity efforts. The RS800CX monitor was also used to record HRmax.

Stroke volume (SV) was estimated using two independent methods. The first method estimated SV from VO_2 and the second from post-exercise blood pressure. As the first method was dependent on VO_2, we used the second method to verify the first but interpreted the result with caution as post-exercise blood pressure can be volatile. The first involved a model based on the Fick principle in which we used VO_2 and HR measured in the last phase of graded exercise test when VO_2max was attained (Stringer et al. 1997). The equation reads:

$$SV = \left(\frac{\frac{VO_2max}{16,22}}{HR} \right) \times 100$$

where SV—stroke volume (ml), VO_2max—maximal oxygen uptake in the graded exercise test (ml min^{-1}), HR—heart rate at VO_2max in the graded exercise test (beats min^{-1}).

The second method employed post-exercise diastolic pressure, pulse pressure (the difference between systolic and diastolic blood pressure) and participant age (Jackson 1955). Here, blood pressure was recorded using an aneroid sphygmomanometer (Riester, Germany) in the first minute of recovery after the graded exercise test was completed when the participant was still sitting on the ergometer. Blood pressure was taken by the same individual by placing the sleeve of the sphygmomanometer on the left arm. SV was estimated based on the equation:

$$SV = 101 + (0.50 \times \text{pulse pressure}) - (0.59 \times \text{diastolic pressure}) - (0.61 \times \text{age})$$

where SV—stroke volume (ml), pulse pressure—the difference between post-exercise systolic and diastolic blood pressure (mm Hg), diastolic pressure—post-exercise (mm Hg), age—(years).

Data analysis

The Statistica 10.0 software package (StatSoft, USA) was used for data processing. Arithmetic means and standard deviations were calculated. A two-way mixed model ANOVA (two groups × two time) was used to analyse the main effects and interaction. When significant changes were obtained, additionally the post hoc Duncan test was used to identify all interactions (in time and between groups). The significance level for all statistical procedures was set at $P = 0.05$. Pearson's correlation coefficients were calculated to determine the strength of associations between VO_2max and the physiological variables and work output obtained in the graded exercise test. Correlations were determined for the entire sample (groups I and E combined), and for each group separately.

Results

Upon completing the 8-week training programs, a statistically significant increase in work output was observed in both groups I ($P = 0.002$) and E ($P = 0.018$) although group I showed a greater magnitude of change (Table 2). In group I, significant increases were also noted for VO_2max ($P = 0.004$), maximal VE ($P = 0.012$) and SV, the latter estimated from VO_2 ($P = 0.022$) and blood pressure ($P = 0.003$). No difference was found for pre- and post-training HRmax in either group. Significant post-training differences between the groups were found in VEmax and SV estimated from blood pressure (Table 2).

Significant correlations were obtained for the entire group (groups I and E combined) between VO_2max and maximal VE ($r = 0.46$, $P < 0.05$); VO_2max and SV estimated from oxygen uptake and heart rate ($r = 0.76$, $P < 0.05$) and VO_2max and SV estimated from blood pressure ($r = 0.39$, $P < 0.05$).

Analysis of the inter-individual differences in group I showed that VO_2max increased in each participant by approximately 4.7–13.8 ml kg^{-1} min^{-1}. The mean increase in VO_2max was 8.7 ml kg^{-1} min^{-1} or 15 % (Fig. 1). No corresponding increase in VO_2max was observed in group E. Inter-individual analysis showed increased oxygen uptake in eight individuals (by approximately 1.9–6.1 ml kg^{-1} min^{-1}) but a decrease in five cyclists (by approximately 0.3–6.6 ml kg^{-1} min^{-1}) (Fig. 2).

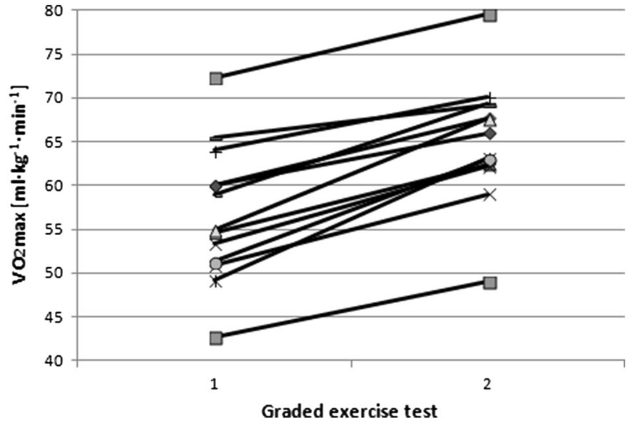

Fig. 1 Inter-individual differences in VO_2max pre- and post-interval/endurance training (group I)

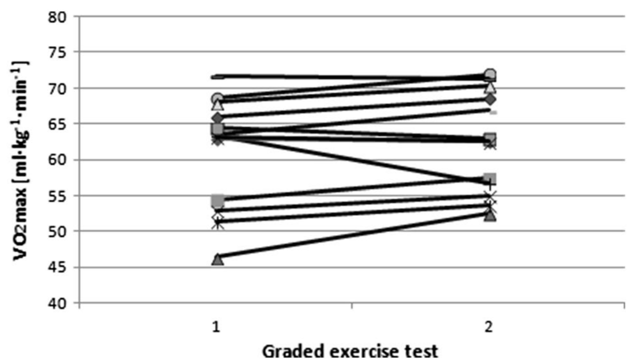

Fig. 2 Inter-individual differences in VO_2max pre- and post-endurance training (group E)

Discussion

Our findings indicate that a combined endurance and interval training protocol is more effective in increasing VO_2max than endurance training alone in MTB cyclists. Only group I showed such a marked improvement in VO_2max (by approximately 15 %). It is highly probable that this training adaptation is the result of the two types of interval training protocols (sprint interval training and high-intensity interval training) that were applied and that training load was individually adjusted to each participant to generate the most effective training effects. Additionally, only group I showed significant increases in maximal VE and estimated SV, both of which affect the VO_2max. The only variable to increase post-training in both groups I and E was work output, improving by 10.4 and 4.2 %, respectively.

Roxburgh et al. (2014) compared the effects of HIIT and endurance training on VO_2max in sedentary adults. While improvements in maximal oxygen uptake were observed after both training modalities, the group performing both endurance and interval training showed an increase in VO_2max by 10.1 %, whereas endurance training alone was responsible for a 3.9 % increase. Such a dynamic improvement in VO_2max among sedentary or untrained individuals has been confirmed in numerous studies (Bouchard et al. 2011; Metcalfe et al. 2012). The literature shows that such results cannot be translated for athletes with several years training experience. This is especially the case for athletes whose training routines involve only endurance-based exercise, where studies have indicated that it is difficult to increase VO_2max in this population (Laursen and Jenkins 2002; Sloth et al. 2013).

Metcalfe et al. (2012) observed increases in VO_2max about 15 % in males and 13 % in females after HIIT, although this was also observed in individuals leading a sedentary lifestyle. Other studies have shown smaller gains, where an interval training intervention for inactive or recreationally active individuals improved VO_2max by approximately 4–13 % (Roxburgh et al. 2014; Sloth et al. 2013). In an athletic population, the concomitant application of endurance and interval training was found to increase VO_2max by only 1–7 % (Creer et al. 2004; Laursen and Jenkins 2002; Smith et al. 1999). However, all of the cited studies involved either sprint interval training or high-intensity interval training, never both. Additionally, these works utilised a rigid interval training protocol for all participants using a fixed number of repetitions (4–8) involving 30 s to 5 min of exercise interspersed with predetermined rest periods (1–5 min) (Creer et al. 2004; Laursen and Jenkins 2002; Smith et al. 1999).

Sloth et al. (2013) compared the results of various interval training strategies to conclude that sprint (all-out) interval training induced better training effects on VO_2max than when using HIIT alone. They found that generating peak power in the first few seconds of sprint exercise leads to more physiological adaptations (due to increased use of the glycolytic and phosphocreatine pathways) than maintaining a constant, high (but not maximal) level of power during a short bout of exercise. The ability to rapidly generate high power in sprint exercise is also associated with a high level of muscle fibre recruitment. Since training intensity in interval training exceeds VO_2max, increased recruitment leads to augmented adaptations among not only the anaerobic enzymes in type II fibres but also aerobic enzyme activity (Bailey et al. 2009). Hence, the application of sprint training even in highly trained athletes is believed to induce significant improvements in aerobic capacity as measured by VO_2max (Sloth et al. 2013).

One of the other previously mentioned determinants of VO_2max is cardiac output, which is a function of heart rate and stroke volume (Trilk et al. 2011; Wagner 2006; Warburton and Gledhill 2006). According to various sources, high-intensity training produces a stronger effect on stroke volume than continuous moderate-intensity training as the increase in blood returning to the heart stretches the ventricles to a greater extent, thereby forcing stronger contractions (Morris-Thurgood and Frenneaux 2000; Stray-Gundersen et al. 1986; Trilk et al. 2011).

Another determinant of VO_2max is VE (Warburton and Gledhill 2006). Studies have found that sprint interval training improves maximal pulmonary ventilation (McKenna et al. 1997) to a greater extent than traditional endurance training in trained athletes (Laursen and Jenkins 2002; Sloth et al. 2013). This has been explained by increases in blood H^+ concentration, partial pressure of oxygen (pO_2) and partial pressure of carbon dioxide (pCO_2), all of which stimulate blood chemoreceptors (Kumar and Bin-Jaliach 2007). As a result, by increasing the accumulation of post-exercise metabolites, this training modality may have provoked an enhanced respiratory response.

Other authors have highlighted the role of skeletal muscle oxidative enzyme activities on VO_2max, such as succinate dehydrogenase and citrate synthase, or the development of blood capillaries and mitochondrial volume density (Henriksson and Reitman 1977). Some investigations reported an increase in enzyme activity after just 2 weeks of interval training, where a similar result was obtained only after 10–12 weeks of endurance training (Blomstrand et al. 2011; Burgomaster et al. 2005, 2008; Gollnick et al. 1973; Green et al. 1991; Henriksson and Reitman 1977; Perry et al. 2010). It is, therefore, highly likely that the metabolic adaptations brought on by interval training stimulate rapid improvement in VO_2max.

There is also evidence that increased VO_2max via interval training more efficiently translates into augmented work output than endurance training, such as by 10.1 and 7.5 % in recreationally active and 11.1 and 3 % in sedentary individuals, respectively (Gibala et al. 2006; Roxburgh et al. 2014). However, research involving highly trained athletes showed far smaller gains in work output via interval training (Laursen and Jenkins 2002; Sloth et al. 2013). Nonetheless, the superior gains in fitness performance afforded by the inclusion of interval training in an endurance-based training program attest to the effectiveness of this training modality in both trained and untrained populations. This is compounded by the fact that interval training involves lower training volume, finding it to be a time-efficient exercise strategy. Lastly, as indicated in this study, of particular importance is the modulation of interval training strategies (sprint interval training and high-intensity interval training) and the individual adjustment of training load to induce the most effective performance adaptations.

Conclusions

An exercise protocol involving endurance and sprint and high-intensity interval training induced greater positive effects on VO_2max as well as maximal exercise performance than an exercise program involving conventional endurance training in well-trained MTB cyclists with several years athletic experience.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Ethical approval All procedures involving human participants were performed in accordance with the ethical standards of the institutional research committee and 1964 Declaration of Helsinki and its later amendments.

Informed consent Informed consent was obtained from all individual participants included in the study.

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