High-Intensity Interval Training, Solutions to the Programming Puzzle

Part I: Cardiopulmonary Emphasis

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Abstract High-intensity interval training (HIT), in a variety of forms, is today one of the most effective means of improving cardiorespiratory and metabolic function and, in turn, the physical performance of athletes. HIT involves repeated short-to-long bouts of rather high-intensity exercise interspersed with recovery periods. For team and racquet sport players, the inclusion of sprints and all-out efforts into HIT programmes has also been shown to be an effective practice. It is believed that an optimal stimulus to elicit both maximal cardiovascular and peripheral adaptations is one where athletes spend at least several minutes per session in their ‘red zone,’ which generally means reaching at least 90 % of their maximal oxygen uptake ($\text{VO}_2\text{max}$). While use of HIT is not the only approach to improve physiological parameters and performance, there has been a growth in interest by the sport science community for characterizing training protocols that allow athletes to maintain long periods of time above 90 % of $\text{VO}_2\text{max}$ ($\text{T@VO}_2\text{max}$). In addition to $\text{T@VO}_2\text{max}$, other physiological variables should also be considered to fully characterize the training stimulus when programming HIT, including cardiovascular work, anaerobic glycolytic energy contribution and acute neuromuscular load and musculoskeletal strain. Prescription for HIT consists of the manipulation of up to nine variables, which include the work interval intensity and duration, relief interval intensity and duration, exercise modality, number of repetitions, number of series, as well as the between-series recovery duration and intensity. The manipulation of any of these variables can affect the acute physiological responses to HIT. This article is Part I of a subsequent II-part review and will discuss the different aspects of HIT programming, from work/relief interval manipulation to the selection of exercise mode, using different examples of training cycles from different sports, with continued reference to $\text{T@VO}_2\text{max}$ and cardiovascular responses. Additional programming and periodization considerations will also be discussed with respect to other variables such as anaerobic glycolytic system contribution (as inferred from blood lactate accumulation), neuromuscular load and musculoskeletal strain (Part II).

1 Introduction

With respect to prescribing training that improves performance, coaches know that ‘there’s more than one way to skin the cat.’ [1] Recent reviews [1, 2] have highlighted the potential of varying quantities of both high-intensity interval training (HIT) and continuous high-volume, low-intensity training on performance in highly trained athletes. While there is no doubt that both types of training can effectively improve cardiac and skeletal muscle metabolic function, and that a dose of both types of training are important constituents of an athlete's training programme,
this review will focus solely on the topic of HIT. Indeed, a
number of studies in this area have emerged over the last
decade, and it is perhaps not surprising that running- or
cycling-based HIT is today considered one of the most
effective forms of exercise for improving physical perfor-
ance in athletes [3–6]. “HIT involves repeated short-to-
long bouts of rather high-intensity exercise interspersed
with recovery periods” [3], and has been used by athletes
for almost a century now. For example, in 1920, Paavo
Nurmi, one of the best middle- and long-distance runners in
the world at that time, was already using some form of HIT
in his training routines. Emil Zatopek contributed later in
the 1950s to the popularization of this specific training
format (see Billat [3] for a detailed history of HIT). The
progressive emergence of this training method amongst
elite athletes is the first evidence of its effectiveness (i.e.
‘best practice’ theory [2]). More recently, the use of sprints
and all-out efforts has also emerged, both from the applied
(team sport) field and the laboratory [7–9]. These par-
ticularly intense forms of HIT include repeated-sprint training
(RST; sprints lasting from 3 to 7 s, interspersed with
recovery periods lasting generally less than 60 s) or sprint
interval training (SIT; 30 s all-out efforts interspersed with
2–4 min passive recovery periods).

Following pioneering experiments by Hill in the 1920s
(Hill included intermittent exercises in his first studies [2]),
Astrand and co-workers published several classical papers
in the 1960s on the acute physiological responses to HIT,
which created the first scientific basis for long [10] and
followed in the 1990s, emphasizing all-out efforts [13]. As
will be detailed in the review, most of the scientific work
that followed these studies over the past 20–50 years has
been an extension of these findings using new technology
in the field (i.e. more accurate and portable devices). How-
ever, the important responses and mechanisms of HIT
had already been demonstrated [10–13].

It has been suggested that HIT protocols that elicit
maximal oxygen uptake (VO_{2max}), or at least a very high
percentage of VO_{2max}, maximally stress the oxygen trans-
port and utilization systems and may therefore provide the
most effective stimulus for enhancing VO_{2max} [5, 14, 15].
While evidence to justify the need to exercise at such an
intensity remains unclear, it can be argued that only exer-
cise intensities near VO_{2max} allow for both large motor unit
recruitment (i.e. type II muscle fibres) [16, 17] and attai-
nement of near-to-maximal cardiac output (see Sect.
3.2), which, in turn, jointly signals for oxidative muscle
fibre adaptation and myocardium enlargement (and hence,
VO_{2max}). For an optimal stimulus (and forthcoming car-
diovascular and peripheral adaptations), it is believed that
athletes should spend at least several minutes per HIT
session in their ‘red zone,’ which generally means attaining
an intensity greater than 90 % of VO_{2max} [3, 5, 15, 18].
Consequently, despite our limited understanding of the
dose-response relationship between the training load and
training-induced changes in physical capacities and per-
formance (which generally shows large inter-individual
responses [19, 20]), there has been a growing interest by
the sport science community for characterizing training
protocols that allow athletes to maintain the longest time
>90 % VO_{2max} (T@VO_{2max}; see Midgley and McNaught-
ton [14] for review). In addition to T@VO_{2max}, however,
other physiological variables should also be considered to
fully characterize the training stimulus when programming
HIT [21–23]. Any exercise training session will challenge,
at different respective levels relative to the training content,
both the metabolic and the neuromuscular/musculoskeletal
systems [21, 22]. The metabolic system refer to three dis-
tinct yet closely related integrated processes, including (1)
the splitting of the stored phosphagens (adenosine tri-
phosphate [ATP] and phosphocreatine [PCr]); (2) the
non-aerobic breakdown of carbohydrate (anaerobic glyco-
ytic energy production); and (3) the combustion of car-
bohydrates and fats in the presence of oxygen (oxidative
metabolism, or aerobic system) [184]. It is therefore pos-
sible to precisely characterize the acute physiological
responses of any HIT session, based on (a) the respective
contribution of these three metabolic processes; (b) the
neuromuscular load; and (c) the musculoskeletal strain
(Fig. 1, Part I). Under these assumptions, we consider the
cardiorespiratory (i.e. oxygen uptake; VO_{2}) data, but also
cardiovascular work [24–27]), stored energy [28, 29] and
cardiac autonomic stress [30–33] responses as the primary
variables of interest when programming HIT sessions
(review Part I). By logic, anaerobic glycolytic energy
contribution and neuromuscular load/musculoskeletal strain are therefore likely the more important secondary
variables to consider when designing a given HIT session
(Part II).

Several factors determine the desired acute physiological
response to an HIT session (and the likely forthcoming adap-
tations) [Fig. 1]. The sport that the athlete is involved in
(i.e. training specificity) and the athlete’s profile or sport
specialty (e.g. an 800 m runner will likely favour a greater
proportion of ‘anaerobic-based’ HIT compared with a
marathon runner [6]) should first be considered in relation to
the desired long-term training adaptations. Second, and
more importantly on a short-term basis, training periodi-
zation has probably the greatest impact on the HIT pre-
scription. Many of the desired training adaptations are
likely training cycle dependent (e.g. generic aerobic power
development in the initial phase of the preseason vs. sport-
specific and more anaerobic-like HIT sessions towards the
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Fig. 1 Decision process for selecting an HIT format based on the expected acute physiological response/strain. The six different types of acute responses are categorized as (1) metabolic, but eliciting essentially large requirements from the O₂ transport and utilization systems, i.e. cardiopulmonary system and oxidative muscle fibres; (2) metabolic as for (1) but with a certain degree of neuromuscular strain; (3) metabolic as for (1) but with a large anaerobic glycolytic energy contribution; (4) metabolic as for (3) plus a certain degree of neuromuscular load; (5) metabolic with essentially an important anaerobic glycolytic energy contribution and a large neuromuscular load; and (6) eliciting a high predominant neuromuscular strain. While some HIT formats can be used to match different response categories (e.g. short intervals when properly manipulated can match into categories 1–4), SIT for example can only match category 5. Category 6 is not detailed in the present review since it does not fit into any particular type of HIT. HIT high-intensity interval training; [La] blood lactate accumulation; surrogate of anaerobic glycolytic energy release; RST repeated-sprint training; SIT spring interval training.

At least nine variables can be manipulated to prescribe different HIT sessions (Fig. 2 [35]). The intensity and duration of work and relief intervals are the key influencing factors [10, 12]. Then, the number of intervals, the number of series and between-series recovery durations and intensities determine the total work performed. Exercise modality (i.e. running vs. cycling or rowing, or straight line vs. uphill or change of direction running) has to date received limited scientific interest, but it is clear that it represents a key variable to consider when programming HIT, especially for team and racquet sport athletes. The manipulation of each variable in isolation likely has a direct impact on metabolic, cardiopulmonary and/or neuromuscular responses. When more than one variable is manipulated simultaneously, responses are more difficult to
Fig. 2 Schematic illustration of the nine variables defining a HIT session adapted from Buchheit [35]. HIT high-intensity interval training

predict, since the factors are inter-related. While our understanding of how to manipulate these variables is progressing with respect to T@\(\dot{V}O_{2\text{max}}\) [14], it remains unclear which combination of work-interval duration and intensity, if any, is most effective at allowing an individual to spend prolonged T@\(\dot{V}O_{2\text{max}}\) while ‘controlling’ for the level of anaerobic engagement [3] and/or neuromuscular load (review Part II).

Considering that long-term physiological and performance adaptations to HIT are highly variable and likely population-dependent (age, gender, training status and background) [19, 20], providing general recommendations for the more efficient HIT format is difficult. We provide, however, in Part I of this review, the different aspects of HIT programming, from work/relief interval manipulation to the selection of exercise modality, with continued reference to T@\(\dot{V}O_{2\text{max}}\) (i.e. time spent \(\geq 90\% \dot{V}O_{2\text{max}}\), otherwise stated), which may assist to individualize HIT prescription for different types of athletes. Additional programming considerations will also be discussed with respect to other variables, such as cardiovascular responses. Different examples of training cycles from different sports will be provided in Part II of the present review. As this was a narrative, and not a systematic review, our methods included a selection of the papers we believed to be most relevant in the area. Since the main goal of HIT sessions is to improve the determinants of \(V\dot{O}_{2\text{max}}\), only HIT sessions performed in the severe intensity domain (i.e. greater than the second ventilatory threshold or maximal lactate steady state) were considered. Acute responses to running-based HIT were given priority focus, since the largest quantity of literature has used this exercise mode. It is likely, however, that the manipulation of these same HIT variables has comparable effects in other sports (or exercise modes, e.g. cycling, rowing, etc.), with the exception of under-water activities that may require a specific programming approach [36]. Finally, we believe that the present recommendations are essentially appropriate for moderately trained to elite athletes. For special populations (e.g. sedentary or cardiac patients), the reader is referred to recent reviews [37] and original investigations [38–40]. Standardized differences (or effect sizes; ES [41]) have been calculated where possible to examine the respective effects of the manipulation of each HIT variable, and interpreted using Hopkins’ categorization criteria, where 0.2, 0.6, 1.2 and >2 are considered ‘small’, ‘medium’, ‘large’ and ‘very large’ effects, respectively [42].

2 Prescribing Interval Training for Athletes in the Field

To prescribe HIT and ensure that athletes reach the required intensity, several approaches exist to control and individualize exercise speed/power accordingly. We will discuss these points and illustrate why, in our opinion, using incremental test parameters is far more objective, practical, and likely more accurate and effective at achieving desired performance outcomes.

2.1 The Track-and-Field Approach

To programme HIT for endurance runners, coaches have traditionally used specific running speeds based on set times for distances ranging from 800 m to 5000 m, but without using physiological markers such as the speeds
associated with $\dot{V}O_{2\text{max}}$, lactate or ventilatory thresholds [3]. It is worth mentioning, however, that coaches and athletes have been, and still are, highly successful using this approach; an observation that should humble the exercise physiologist. The attraction of this method is that the entire locomotor profile (i.e. both maximal sprinting and aerobic speeds, Fig. 3) of the athlete can be used to ‘shape’ the HIT session, so that each run can be performed in accordance with the athlete’s (maximal) potential. While for short intervals (i.e. 10–60 s) the reference running time will be a percentage of the time measured over a maximal 100–400 m sprint, the speed maintained over 800–1,500 m to 2,000–3,000 m can be used to calibrate longer intervals (e.g. 2–4 to 6–8 min). The disadvantage of this approach, however, is that it does not allow the coach to consciously manipulate the acute physiological load of the HIT session, and precisely target a specific adaptation (i.e. Fig. 1, when there is a need to improve a physiological quality and not just to prepare for a race). Additionally, this approach tends to be reserved for highly experienced coaches and well-trained athletes, for whom best running times on several set distances are known. The translation and application of the track-and-field method to other sports is, however, difficult. For example, how might a coach determine the expected 800-m run time for a 2.10-m tall basketball player that has never run more that 40 s continuously on a court before? Thus, using the track-and-field approach for non-track-and-field athletes is unlikely to be appropriate, practical or effective.

2.2 The Team Sport Approach

Due to the technical/tactical requirements of team sports, and following the important principle of training specificity, game- (i.e. so-called small sided games, SSG) [43–46] or skill-based [47, 48] conditioning has received an exponential growth in interest [49]. While understanding of the $\dot{V}O_2$ responses to SSG is limited [44, 50, 51], T@$\dot{V}O_{2\text{max}}$ during an SSG in national-level handball players was achieved for 70 % of the session (i.e. 5 min 30 s of the 8-min game) [50]. Although the effectiveness of such an approach has been shown [43, 46, 52, 53]; SSGs have limitations that support the use of less specific (i.e. run based) but more controlled HIT formats at certain times of the season or for specific player needs. The acute physiological load of an SSG session can be manipulated by changing the technical rules [54], the number of players and pitch size [55], but the overall load cannot, by default, be precisely standardized. Within-player responses to SSG are highly variable (poor reproducibility for blood lactate [coefficient of variation (CV): 15–30 %] and high-intensity running responses [CV: 30–50 %] [56, 57]), and the between-player variability in the (cardiovascular) responses is higher than more specific run-based HIT [49]. During an SSG in handball, average $\dot{V}O_2$ was shown to be inversely related to $\dot{V}O_{2\text{max}}$ [50], suggesting a possible ceiling effect for $\dot{V}O_{2\text{max}}$ development in fitter players. Additionally, reaching and maintaining an elevated cardiac filling is believed to be necessary to improve maximal cardiac

![Fig. 3 Intensity range used for the various run-based HIT formats. ASR anaerobic speed reserve, MLSS maximal lactate steady state, MSS maximal sprinting speed, RST repeated-sprint training, SIT sprint interval training, $\dot{V}O_{2\text{max}}$ maximal oxygen uptake, $\dot{V}O_{2\text{max}}$ minimal running speed required to elicit $\dot{V}O_{2\text{max}}$, $V_{30}$ speed half way between $\dot{V}O_{2\text{max}}$ and MLSS, $V_{\text{crit}}$ critical velocity, $V_{\text{IFT}}$ peak speed reached at the end of the 30–15-Interval Fitness Test, $V_{\text{inc Test}}$ peak incremental test speed.](attachment:fig3.png)
function [58, 59]. The repeated changes in movement patterns and the alternating work and rest periods during an SSG might therefore induce variations in muscular venous pump action, which can, in turn, limit the maintenance of a high stroke volume (SV) throughout the exercise and compromise long term adaptations [60] (see Sect. 3.2). Compared with generic run-based exercises, the VO2/heart rate (HR) ratio (which can be used with caution as a surrogate of changes in SV during constant exercise when the arteriovenous O2 difference is deemed constant [61]) is also likely lower during an SSG [44, 50, 51]. While this ratio is generally close to 1 during run-based long intervals (i.e. VO2 at 95 % VO2max for HR at 95 % of maximal HR (HRmax) [21, 62]), authors have reported values at 79 % VO2max and 92 % HRmax during basketball drills [44] and at 52 % VO2max and 72 % HRmax during a five-a-side indoor soccer game [51]. This confirms the aforementioned possible limitations with respect to SV enlargement, and suggests that assessment of cardiopulmonary responses during an SSG (and competitive games) using HR may be misleading [63]. Finally, the VO2/speed [50] (and HR/speed [63]) relationship also tends to be higher during an SSG compared with generic running, possibly due to higher muscle mass involvement. While this method of training is often considered to be highly specific, this is not always the case, since during competitive games players have often more space to run and reach higher running speeds (up to 85–90 % of maximal sprinting speed [64–66]) for likely similar metabolic demands.

2.3 Heart Rate-Based Prescription

Heart rate has become the most commonly measured physiological marker for controlling exercise intensity in the field [67]. Setting exercise intensity using HR zones is well suited to prolonged and submaximal exercise bouts; however, its effectiveness for controlling or adjusting the intensity of an HIT session may be limited. HR cannot inform the intensity of physical work performed above the speed/power associated with VO2max, which represents a large proportion of HIT prescriptions [3–5]. Additionally, while HR is expected to reach maximal values (>90–95 % HRmax) for exercise at or below the speed/power associated with VO2max, this is not always the case, especially for very short (<30 s) [68] and medium-long (i.e. 1–2 min) [69] intervals. This is related to the well-known HR lag at exercise onset, which is much slower to respond compared with the VO2 response [70]. Further, HR inertia at exercise cessation (i.e. HR recovery) can also be problematic in this context, since this can create an overestimation of the actual work/physiological load that occurs during recovery periods [69]. It has also been shown that substantially different exercise sessions (as assessed by accumulated blood lactate levels during run-based HIT [71] and by running speed during an SSG [63]) can have a relatively similar mean HR response. Thus, the temporal dissociation between HR, VO2, blood lactate levels and work output during HIT limits our ability to accurately estimate intensity during HIT sessions using HR alone. Further, it is difficult to imagine how an athlete would practically control or adjust exercise intensity during an interval, especially for athletes running at high speed, where viewing HR from a watch is difficult.

2.4 Rating of Perceived Exertion-Based Prescription

Prescribing the intensity of HIT bouts using the rating of perceived exertion (RPE) method [72] is highly attractive because of its simplicity (no need to monitor HR) and versatility. Using this approach, coaches generally prescribe independent variables such as the duration or distance of work and relief intervals [71]. In return, the athlete can self-regulate their exercise intensity. The intensity selected is typically the maximal intensity of exercise perceived as sustainable (‘hard’ to ‘very hard’, i.e. ≥6 on a CR-10 Borg scale and ≥15 on a 6–20 scale) and is based on the athlete’s experience, the session goal and external considerations related to training periodization. While the specific roles (or contributions) played by varying biological afferents and other neurocognitive processes involved with the selection of exercise pace based on effort are still debated (see viewpoint/counterpoint [73]), RPE responses may reflect “a conscious sensation of how hard, heavy, and strenuous exercise is” [74], relative to the combined physiological [75], biomechanical and psychological [76] stress/fatigue imposed on the body during exercise [77]. RPE responses are gender-independent [78] and comparable during free versus constant pace exercise [79]. In practice, the first benefit of RPE-guided HIT sessions [69, 71] is that they do not require any knowledge of the athletes’ fitness level (no test results needed). Finally, RPE is a universal ‘exercise regulator’, irrespective of locomotor mode and variations in terrain and environmental conditions. While more research in trained athletes is needed to confirm the efficacy of RPE-guided training sessions, it has been shown to promote the same physiological adaptations as an HR-based programme over 6 weeks in young women [80]. The RPE method does have limitations, however, since it does not allow for the precise manipulation of the physiological response to a given HIT session. This could limit the ability to target a specific adaptation (i.e. Fig. 1), and might also be problematic in a team sport setting (as discussed in the three preceding sections). There is also some evidence to suggest that the ability to adjust/evaluate
exercise intensity based on RPE may be age- [81], fitness-
[82, 83], exercise-intensity- and pleasure-[84] dependent.

2.5 Velocity/Power Associated with Maximal Oxygen
Uptake (V\textsubscript{O\textsubscript{2max}})

Following early works in the 1970s and 1980s [85-88], the
physiologists V.L. Billat and D.W. Hill popularized the speed
(or power) associated with V\textsubscript{O\textsubscript{2max}} (so-called
v/p\textsubscript{V\textsubscript{O\textsubscript{2max}}} or maximal aerobic speed/power [MAS/MAP]
[89, 90]) as a useful reference intensity to programme HIT
[3-5]. The attractiveness of the v/p\textsubscript{V\textsubscript{O\textsubscript{2max}}} method is that it
represents an integrated measure of both V\textsubscript{O\textsubscript{2max}} and the
energetic cost of running/cycling into a single factor; hence,
being directly representative of an athletes’ locomo-
motor ability [89]. Since v/p\textsubscript{V\textsubscript{O\textsubscript{2max}}} is theoretically the
lowest speed/power needed to elicit V\textsubscript{O\textsubscript{2max}}, it makes
intuitive sense for this marker to represent an ideal refer-
ence for training [5, 15, 89].

v/p\textsubscript{V\textsubscript{O\textsubscript{2max}}} can be determined, or estimated, a number of
different ways. Methods include using the following:

1) The linear relationship between V\textsubscript{O\textsubscript{2}} and running
speed established at submaximal speeds [88].

2) The individual cost of running to calculate a theoreti-
cal running speed for a given V\textsubscript{O\textsubscript{2max}}, either with [91]
or without [92] resting V\textsubscript{O\textsubscript{2}} values.

3) Direct measurement (i.e. pulmonary gas exchange
[93]) during ramp-like incremental running/cycling
tests to exhaustion, either on the track, on a treadmill
or using an ergometer. On the track, the University of
Montreal Track Test (UM-TT [87]) is the protocol
most commonly used with athletes [94, 95], although
the Vam-Eval [96], which only differs from the UM-
TT due to its smoother speed increments and shorter
intercones distances, has also received growing inter-

test since it is easier to administer in young populations
and/or non-distance running specialists [97, 98]. Since
the ‘true’ v/p\textsubscript{V\textsubscript{O\textsubscript{2max}}} during incremental tests requires
V\textsubscript{O\textsubscript{2}} measures to determine the lowest speed/power
that elicits V\textsubscript{O\textsubscript{2max}} (generally defined as a plateau in
V\textsubscript{O\textsubscript{2}} or an increase less than 2.1 mL/min/kg despite an
increase in running speed of 1 km/h [93]), the final
(peak) incremental test speed/power reached at the end
of these tests (V\textsubscript{int Test}) is only an approximation of
v/p\textsubscript{V\textsubscript{O\textsubscript{2max}}}. These two distinct speeds/powers are
strongly correlated (r > 0.90 [87]), but V\textsubscript{int Test} can be
5-10 % greater than v/p\textsubscript{V\textsubscript{O\textsubscript{2max}}}, with individuals
possessing greater anaerobic reserves presenting gen-
erally a greater v/p\textsubscript{V\textsubscript{O\textsubscript{2max}}}- V\textsubscript{int Test} difference. Measurement of V\textsubscript{int Test} is, however, very practical in

the field since it is largely correlated with distance
running performance [99] and match running capacity
in team sports (but for some positions only) [98, 100].

4) A 5-min exhaustive run [101], since the average time
to exhaustion at vVO\textsubscript{2max} has been reported to range
from 4 to 8 min [89, 102]. The vVO\textsubscript{2max} calculated
from this test has been shown to be largely correlated
with the V\textsubscript{int Test} reached in the UM-TT (r = 0.94)
and on a ramp treadmill test (r = 0.97) [101], while
being slightly (i.e. 1 km/h range) slower and faster
than these velocities, respectively. The vVO\textsubscript{2max}
estimated via the 5-min test is, however, likely
influenced by pacing strategies, and may only be valid
for trained runners able to run at vV\textsubscript{O\textsubscript{2max}} for ±5 min.

vVO\textsubscript{2max} is also method-[90] and protocol-dependent
[103]. A mathematically estimated vVO\textsubscript{2max} [88, 91] is
likely to be lower than a measured vVO\textsubscript{2max} [93] that is
also lower than V\textsubscript{int Test} [89, 104]. Additionally, irrespec-
tive of the method used to determine vVO\textsubscript{2max}, protocols
with longer-stage durations tend to elicit lower speed/
power values [103], while larger speed/power increments
result in higher-speed/power values. Similarly, vVO\textsubscript{2max}
also appears to be inversely related to the terrain or
treadmill slope [105]. Endurance-trained athletes are likely
able to tolerate longer stages and therefore, less likely to
present impairments in vVO\textsubscript{2max} with variations in proto-

col. These differences must be acknowledged since small
differences in the prescribed work intensity have sub-
stantial effects on acute HIT responses.

The reliability of vVO\textsubscript{2max} and V\textsubscript{int Test} (as examined
using CVs) has been shown to be good: 3 % for vVO\textsubscript{2max}
in moderately trained middle- and long-distance runners
[68], 3.5 % for UM-TT V\textsubscript{int Test} in moderately trained
athletes [87], 3.5 % (90 % confidence limits: 3.0, 4.1
[Buchheit M, unpublished results]) for Vam-Eval V\textsubscript{int Test}
in 65 highly trained young football players, 2.5 % and 3 %
for treadmill V\textsubscript{int Test} in well trained male distance runners
[106] and recreational runners [104], respectively, and
finally, 1–2 % for the 5-min test in a heterogeneous
sporting population [107].

For training prescription, V\textsubscript{int Test}, as determined in the
field with the UM-TT [87] or the Vam-Eval [96], is
probably the preferred method, since, in addition to not
requiring sophisticated apparatus, the tests account for the
anaerobic contribution necessary to elicit V\textsubscript{O\textsubscript{2max}} [108]. It
is, however, worth noting that using vV\textsubscript{O\textsubscript{2max}} or V\textsubscript{int Test} as
the reference running speed is essentially suitable for long
(2–6 min) intervals ran around vVO\textsubscript{2max} (90-105 %). For sub-
and supramaximal training intensities, however, the
importance of other physiological attributes should be
considered. For instance, endurance capacity (or the capacity to sustain a given percentage of $\dot{V}O_{2\text{max}}$ over time [109]) and anaerobic power/capacity [110] are likely to influence time to exhaustion and, in turn, the physiological responses. The following section highlights the different options available for the prescription of supramaximal training (i.e., training at intensities $> \dot{V}O_{2\text{max}}$).

### 2.6 Anaerobic Speed Reserve

Consideration for an individual’s anaerobic speed reserve (ASR; the difference between maximal sprinting speed (MSS) and $\dot{V}O_{2\text{max}}$). Fig. 3 is often not fully taken into account by coaches and scientists in their training prescription. While track-and-field (running) coaches have indirectly used this concept for years to set the work interval length (as discussed in Sect. 2.1), its scientific basis and interest was only brought forth merely a decade ago, when Billat and co-workers [110] showed that time to exhaustion at intensities above $\dot{V}O_{2\text{max}}$ were better related to the ASR and/or MSS, than to $\dot{V}O_{2\text{max}}$. Bundle et al. [111–113] demonstrated, using an empirical prediction model, that the proportion of ASR used could determine performance during all-out efforts lasting between a few seconds and several minutes. While these studies have used continuous exercise, ASR has only recently been considered in relation to repeated-sprint performance [114, 115].

In practice, two athletes can present with clearly different MSS ability, despite a similar $\dot{V}O_{2\text{max}}$ (Fig. 4 [116]). If during an HIT session they exercise at a similar percentage of $\dot{V}O_{2\text{max}}$, as is generally implemented in the field (e.g., see [117]), the exercise will actually involve a different proportion of their ASR, which results in a different physiological demand, and in turn, a different exercise tolerance [116]. Therefore, it appears that, in addition to $\dot{V}O_{2\text{max}}$, the measurement of MSS (and ASR) should be considered for individualizing training intensity during supramaximal HIT [110, 116].

### 2.7 Peak Speed in the 30–15 Intermittent Fitness Test

While using the ASR to individualize exercise intensity for supramaximal runs might represent an improved alternative over that of $\dot{V}O_{2\text{max}}$ or $V_{\text{Inc, Test}}$, it still does not capture an overall picture of the different physiological variables of importance during team- or racquet-based specific HIT sessions. In many sports, HIT is performed indoors and includes repeated very short work intervals (< 45 s). This implies that, in addition to the proportion of the ASR used, the responses to these forms of HIT appear related to an individual’s (1) metabolic inertia (e.g., $\dot{V}O_{2}$ kinetics) at the onset of each short interval; (2) physiological recovery capacities during each relief interval; and (3) change of direction ability (since indoor HIT is often performed in shuttles) [94, 116]. Programming HIT without taking these variables into consideration may result in sessions with different aerobic and anaerobic energy demands, which prevents the standardization of training load, and likely limits the ability to target specific physiological adaptations [94]. To overcome the aforementioned limitations inherent with the measurement of $\dot{V}O_{2\text{max}}$ and ASR, the 30–15 Intermittent Fitness Test (30–15 HIT) was developed for intermittent exercise and change of direction (COD)-based HIT prescription [35, 94, 116]. The 30–15 HIT was designed to elicit maximal HR and $\dot{V}O_{2}$, but additionally provide measures of ASR, repeated effort ability, acceleration, deceleration, and COD abilities [94, 118, 119]. The final speed reached during the 30–15 HIT, $V_{\text{HIT}}$ is, therefore a product of those above-mentioned abilities. In other words, the 30–15 HIT is highly specific, not to a specific sport, but to the training sessions commonly performed in intermittent sports [116]. While the peak speeds reached in the different Yo-Yo tests [120] (e.g., $V_{\text{YoyoYoIR1}}$ for the Yo-Yo Intermittent Recovery Level 1) and $V_{\text{HIT}}$ have likely similar physiological requirements [221], only the $V_{\text{HIT}}$ can be used accurately for training prescription. For instance, $V_{\text{YoyoYoIR1}}$ cannot be directly used for training prescription since, in contrast to $V_{\text{HIT}}$ [35], its relationship with $V_{\text{Inc, Test}}$ and $\dot{V}O_{2\text{max}}$ is speed-dependent [121]. Fig. 5. When running at $V_{\text{YoyoYoIR1}}$, slow and unfit athletes use a greater proportion of their ASR, while fitter athletes run below their $\dot{V}O_{2\text{max}}$ (Fig. 5). Finally, $V_{\text{HIT}}$ has been shown to be more accurate than $V_{\text{Inc, Test}}$ for individualizing HIT with COD in well-trained team sport players [94], and its reliability is good, with the typical

![Image](https://example.com/image.png)

**Fig. 4** Illustration of the importance of ASR for two athletes possessing similar running speeds associated with $\dot{V}O_{2\text{max}}$ but different maximal sprinting speeds. During an HIT session, Athlete B with a greater ASR will work at a lower percentage of his ASR, and will therefore achieve a lower exercise load compared with Athlete A [116]. ASR anaerobic speed reserve, HIT high-intensity interval training, $\dot{V}O_{2\text{max}}$ minimal running speeds associated with maximal oxygen uptake.
3 Acute Responses to Variations of Interval Training

3.1 Maximizing the Time Spent at or Near $\dot{V}O_{2\text{max}}$

We lead off this review with data related to $T@\dot{V}O_{2\text{max}}$ (reviewed previously [14]), since pulmonary $\dot{V}O_2$ responses may actually integrate both cardiovascular and muscle metabolic (oxidative) responses to HIT sessions. In the present review, we integrate recently published work and provide a comprehensive analysis of the $\dot{V}O_2$ responses to different forms of HIT, from long intervals to SIT sessions, through short intervals and repeated-sprint sequences (RSS, Fig. 3). Figure 6 illustrates the $\dot{V}O_2$ responses of four distinct HIT sessions, including long intervals, and highlights how changes in HIT variables can impact the $T@\dot{V}O_{2\text{max}}$ [21, 50, 127, 128]. There are, however, numerous methodological limitations that need to be considered to interpret the findings shown from the different studies [68, 103, 129]. In addition to methodological considerations between studies (treadmill vs. overground running, determination criteria for both $\dot{V}O_{2\text{max}}$ and $v\dot{V}O_{2\text{max}}$, data analysis [averaging, smoothing technique], threshold for minimal $\dot{V}O_2$ values considered as maximal [90 %, 95 %, $\dot{V}O_{2\text{max}}$ minus 2.1 ml/min/kg, 100 %]), differences in the reliability level of analysers and intra-day subject variation in $\dot{V}O_{2\text{max}}$, $\dot{V}O_2$ kinetics and times to exhaustion, make comparison between studies difficult. The withholding effects of HIT variable manipulation on the observed $T@\dot{V}O_{2\text{max}}$ can, however, provide insight towards understanding how best to manipulate HIT variables.

3.1.1 Oxygen Uptake ($\dot{V}O_2$) Responses to Long Intervals

3.1.1.1 Exercise Intensity during Long Intervals During a single constant-speed or power exercise, work intensity close to $v/p\dot{V}O_{2\text{max}}$ is required to elicit maximal $\dot{V}O_2$ responses. In an attempt to determine the velocity associated with the longest $T@\dot{V}O_{2\text{max}}$ during a run to exhaustion, six physical-education students performed four separate runs at 90 %, 100 %, 120 % and 140 % of their $v\dot{V}O_{2\text{max}}$ (17 km/h) [130]. Not surprisingly, time to exhaustion was inversely related to running intensity. $T@\dot{V}O_{2\text{max}}$ during the 90 % and 140 % conditions was trivial (i.e. $<20$ s on average), but reached substantially
Fig. 6 Mean ± SD of total session time, T@VO₂max, total distance and distance run above 90% of vVO₂max during four different HIT sessions including long intervals. Percentages (mean ± SD) refer to T@VO₂max relative to the total session time, and distance run above 90% of vVO₂max relative to the total distance run. RPE and [La] mmol/L are provided as mean ± SD when available. References: 1 [21]; 2 [127]; 3 [128] and 4 [50]. HIT high-intensity interval training, [La] blood lactate concentration, N/A not available, RPE rating of perceived exertion, SSG small-sided games (handball), VO₂max maximal oxygen uptake, T@VO₂max time spent above 90% or 95% of VO₂max, vVO₂max minimal running speed associated with VO₂max

‘larger’ values at 100% and 120%: mean ± standard deviation 190 ± 87 (57% of time to exhaustion, ES > +2.8) and 73 ± 29 s (59%, ES > +1.7). In another study, middle-distance runners did not manage to reach VO₂max while running at 92% of vVO₂max [131]. The ability to reach VO₂max during a single run at the velocity between the maximal lactate steady state and vVO₂max (i.e., vΔ50, ≈ 92–93% of vVO₂max [130]) via the development of a VO₂ slow component [10] is likely fitness-dependent [132] (with highly trained runners unlikely to reach VO₂max). In addition, as the determination of vΔ50 is impractical in the field, work intensities of ≥95% v/pVO₂max are therefore recommended for maximizing T@VO₂max during single isolated runs. However, in practice, athletes do not exercise to exhaustion, but use intervals or sets. Slightly lower intensities (≥90% v/pVO₂max) can also be used when considering repeated exercise bouts (as during HIT sessions), since interval VO₂ is likely to increase with repetitions with the development of a VO₂ slow component [10]. As suggested by Astrand in the 1960s [10], exercise intensity does not need to be maximal during an HIT session to elicit VO₂max.

3.1.1.2 Time-to-Reach VO₂max and Maximizing Long-Interval Duration If VO₂max is to be reached during the first interval of a sequence, its interval duration must at least be equal to the time needed to reach VO₂max. Thus, with short intervals, as during typical HIT sessions (work interval duration < time needed to reach VO₂max), VO₂max is usually not reached on the first interval. VO₂max values can, however, be reached during consecutive intervals, through the priming effect of an adequate warm-up and/or the first intervals (that accelerates VO₂ kinetics [133, 134]) and the development of a VO₂ slow component [10]. The time needed to reach VO₂max during constant-speed exercise to exhaustion has received considerable debate in the past [104, 131, 135–138]. The variable has been shown to range from 97 s [138] to 299 s [131] and has a high intersubject variability (20–30% [131, 135, 137] to 40% [104]). While methodological differences could explain some of these dissimilarities (whether 90% or 100% of VO₂max is considered, the presence and type of pretrial warm-up), the variability is consistent with those shown in VO₂ kinetics at exercise onset. VO₂ kinetics are generally affected by exercise intensity [139], accelerated during running compared with cycling exercise [140] and faster in trained individuals [141]. The relationship between VO₂ kinetics at exercise onset and VO₂max, however, is less clear, with some studies reporting relationships [141–143], and others showing no correlation [144–146], suggesting that the VO₂ kinetics at exercise onset is more related to training status [141, 147] than VO₂max per se.
As an alternative to using fixed long-interval durations, using 50–70 % of time to exhaustion at vVO2max has been suggested by the scientific community as an alternative to individualizing interval training [3, 5, 137, 148–150]. However, to our knowledge, prescribing training based on time to exhaustion is very rare compared with how endurance athletes actually train. Additionally, while the rationale of this approach is sound (50–70 % is the average proportion of time to exhaustion needed to reach VO2max), this is not a practical method to apply in the field. First, in addition to vVO2max, time to exhaustion at vVO2max must be determined, which is only a moderately reliable measure (CV = 12 % [68] to 25 % [93]), is exhaustive by nature and highly dependent on the accuracy of the vVO2max determination [103]. Second, the time required to reach VO2max has frequently been reported to be longer than 75 % of time to exhaustion in some participants [131, 135, 136]. Intervals lasting 70 % of time to exhaustion have also been reported as very difficult to perform, likely due to the high anaerobic energy contribution this requires [150]. For athletes presenting with exceptionally long time to exhaustion, repeating sets of 60 % of time to exhaustion is typically not attainable [137]. Finally, there is no link between the time needed to reach VO2max and time to exhaustion [135, 137]. Therefore, since a given percentage of time to exhaustion results in very different amounts of T@VO2max, it appears more logical to use the time needed to reach VO2max to individualize interval length [135] (e.g. time needed to reach VO2max + 1 or 2 min). If the time needed to reach VO2max cannot be determined (as is often the case in the field), we would therefore recommend using fixed intervals durations ≥2–3 min that could be further adjusted in accordance with the athlete’s training status (with the less trained performing lower training loads, but longer intervals) and the exercise mode. Indeed, if we consider that the time constant of the primary phase of the VO2 kinetics at exercise onset (τ) in the severe intensity domain is generally in the range of 20 s to 35 s [131, 140, 146], and that a steady-state (≥95 % VO2max) is reached after exercise onset within ≈4 τ, VO2max should then be reached from within 1 min 20 s to 2 min 20 s (at least when intervals are repeated), irrespective of training status and exercise mode. This is consistent with the data shown by Vuorimaa et al. in national level runners (vVO2max = mean ± SD 19.1 ± 1 km/h), where VO2max values were reached during 2-min work/2-min rest intervals, but not during 1 min/1 min [22]. Similarly, in the study by Seiler and Sjursen [71] in well trained runners (vVO2max = 19.7 ± 1 km/h), peak VO2 was only 82 ± 5 % of VO2max during 1-min intervals, while it reached 92 ± 4 % during 2-min intervals; extending the work duration did not modify these peak values (93 ± 5 and 92 ± 3 % for 4- and 6-min intervals, respectively). Although performed on an inclined treadmill (5 %), these latter sessions were performed at submaximal self-selected velocities (i.e. 91 %, 83 %, 76 % and 70 % vVO2max for 1-, 2-, 4- and 6-min intervals, respectively [71]), which probably explains why VO2max was not reached [130] (see Sect. 3.1.1.4 below with respect to uphill running).

3.1.1.3 Relief Interval Characteristics during Long-Intervals High-Intensity Interval Training (HIT) When programming HIT, both the duration and intensity of the relief interval are important [152]. These two variables must be considered in light of (1) maximizing work capacity during subsequent intervals (by increasing blood flow to accelerate muscle metabolic recovery, e.g. PCr resynthesis, H+ ion buffering, regulation of inorganic phosphate (Pi) concentration and K+ transport, muscle lactate oxidation) and; (2) maintaining a minimal level of VO2 to reduce the time needed to reach VO2max during subsequent intervals (i.e. starting from an elevated ‘baseline’) [3, 14]. While performing active recovery between interval bouts is appealing to accelerate the time needed to reach VO2max and in turn, induce a higher fractional contribution of aerobic metabolism to total energy turnover [134], its effects on performance capacity (time to exhaustion), and hence, T@VO2max are not straightforward. The benefit of active recovery has often been assessed via changes in blood lactate concentration [153, 154], which has little to do with muscle lactate concentration [155]. Additionally, neither blood [156, 157] nor muscle [155] lactate has a direct (nor linear) relationship with performance capacity. The current understanding is that active recovery can lower muscle oxygenation [158, 159], impair PCr resynthesis (O2 competition) and trigger anaerobic system engagement during the following effort [160]. Additionally, while a beneficial performance effect on subsequent intervals can be expected with long recovery periods (≥3 min [134, 161, 162], when the possible ‘wash out’ effects overcome that of the likely reduced PCr resynthesis), active recovery performed during this period may negate subsequent interval performance using both long periods at high intensities (>45 % v/pVO2max) [153] and short periods of varying intensity [159, 163]. In the context of long interval HIT, passive recovery is therefore recommended when the relief interval is less than 2–3 min in duration. If an active recovery is chosen for the above-mentioned reasons (i.e. [3, 14, 134]), relief intervals should last at least 3–4 min at a submaximal intensity [153] to allow the maintenance of high-exercise intensity during the following interval.

In practice, active recovery is psychologically difficult to apply for the majority of athletes, especially for non-
endurance athletes. When moderately trained runners (v\(\text{VO}_{2\text{max}}\) = 17.6 km/h) were asked to self-select the nature of their relief intervals during an HIT session (6 × 4 min running at 85 % v\(\text{VO}_{2\text{max}}\) on a treadmill with 5 % incline), they chose a walking recovery mode of about 2 min [69]. Compared with 1-min recovery intervals, the 2-min recovery duration enabled runners to maintain higher running speeds; extending passive recovery to 4 min did not provide further benefits with respect to running speeds. The low T@v\(\text{VO}_{2\text{max}}\)/total exercise time ratio shown by Millet et al. [128] (34 % when considering time >90 % v\(\text{VO}_{2\text{max}}\); Fig. 6) in well-trained triathletes (v\(\text{VO}_{2\text{max}}\) = 19.9 ± 0.9 km/h) was likely related to the introduction of 5-min passive pauses every second interval. With intervals performed successively (no passive pauses, no blocks but active recoveries < 50 % v\(\text{VO}_{2\text{max}}\) between runs), Demarie et al. [127] reported a longer T@v\(\text{VO}_{2\text{max}}\) in senior long-distance runners (v\(\text{VO}_{2\text{max}}\) = 16.6 ± 1.1 km/h). More recently, Buchheit et al. showed, in highly trained young runners (v\(\text{VO}_{2\text{max}}\) = 18.6 ± 0.3 km/h), that even shorter recovery periods (i.e. 90 s), despite a passive recovery intensity (walk), enabled athletes to spend a relatively high proportion of the session at >90 % v\(\text{VO}_{2\text{max}}\) (43 %) [21]. This particular high ‘efficiency’ was also likely related to both the young age [222] and the training status [141] of the runners (since both are generally associated with accelerated \(\text{VO}_2\) kinetics).

Finally, in an attempt to individualize between-run recovery duration, the return of HR to a fixed value or percentage of HRR\(_{\text{max}}\) is sometime used in the field and in the scientific literature [165, 166]. The present understanding of the determinants of HR recovery suggest, nevertheless, that this practice is not very relevant [69]. During recovery, HR is neither related to systemic \(\text{O}_2\) demand nor muscular energy turnover [145, 167], but rather to the magnitude of the central command and metaboreflex stimulations [168].

3.1.1.4 Uphill Running during HIT with Long Intervals Despite its common practice [166], the cardiorespiratory responses to field-based HIT sessions involving uphill or staircase running has received little attention. Laboratory studies in trained runners (V\(_{\text{int.cell}}\) ≥ 20 km/h) [170, 171] have shown that, for a given running speed, \(\text{VO}_2\) is higher during uphill compared with level running after a couple of minutes, probably due to the increased forces needed to move against gravity, the subsequently larger motor units recruited and the greater reliance on concentric contractions; all of which are believed initiators of the \(\text{VO}_2\) slow component [172]. However, in practice, athletes generally run slower on hills versus the track [173]. Gajer et al. [174] found in elite French middle-distance runners (v\(\text{VO}_{2\text{max}}\) = mean ± SD 21.2 ± 0.6 km/h; v\(\text{VO}_{2\text{max}}\) = 78 ± 4 mL/min/kg) that T@v\(\text{VO}_{2\text{max}}\) observed during a hill HIT session (6 × 500 m [1 min 40 s] 4–5 % slope [85 % v\(\text{VO}_{2\text{max}}\) at 1 min 40 s [0 %]]) was lower compared with a ‘reference’ track session (6–600 m [1 min 40 s] 102 % v\(\text{VO}_{2\text{max}}\) at 1 min 40 s [0 %]). While \(\text{VO}_2\) reached 99 % and 105 % v\(\text{VO}_{2\text{max}}\) during the hill and track sessions, respectively, the T@v\(\text{VO}_{2\text{max}}\)/exercise time ratio was ‘moderately’ lower during the hill HIT (27 % vs. 44 %, ES = –1.0). The reason for the lower T@v\(\text{VO}_{2\text{max}}\) during the hill HIT is unclear. Despite the expected higher muscle force requirement during hill running [173], this is unlikely enough to compensate for the reduction in absolute running speed. If we consider that running uphill at 85 % v\(\text{VO}_{2\text{max}}\) with a grade of 5 % has likely the same (theoretical) energy requirement as level running (or treadmill running with a 1 % grade to compensate for wind resistance [105]) at ≈ 105 %; [175] the differences observed by Gajer et al. could have been even greater if the flat condition was ran at a faster (and possibly better matched) speed (105 % vs. 102 % [174]). As well, intervals in these sessions might not have been long enough to observe the additional slow component generally witnessed with uphill running (≈ 2 min [172]). More research is required, however, to clarify the cardiorespiratory responses to uphill running at higher gradients (> 10 %) or to staircase running that may require very high \(\text{VO}_2\) values due to participation of upper body limbs (back muscles and arms when pushing down or grabbing handrails).

3.1.1.5 Volume of HIT with Long Intervals Another variable that can be used to maximize T@v\(\text{VO}_{2\text{max}}\) is the number of long-interval repetitions. It is worth noting, however, that very few authors have examined HIT sessions/programmes that are consistent with the sessions that athletes actually perform, and that research on the optimal T@v\(\text{VO}_{2\text{max}}\) per session is limited. Cumulated high-intensity (>90 % v/v\(\text{VO}_{2\text{max}}\)) exercise time during typical sessions in well-trained athletes has been reported to be 12 min (6 × 2 min or 6 × ≈600 m [128], 15 min (5 × 3 min or 5 × ≈800–1,000 m [21]), 16 min (4 × 4 min or 4 × ≈1,000–1,250 m [46]), 24 min (6 × 4 min or 6 × ≈1,000–1,250 m [69]); 4 × 6 min or 4 × ≈1,500 m [71]) and 30 min (6 × 5 min or 5 × ≈1,500–1,700 m [127]), which enabled athletes to accumulate, depending on the HIT format, from 10 min >90 % [21, 128] to 4–10 min >95 % [127, 128] at v\(\text{VO}_{2\text{max}}\). Anecdotal evidences suggest that elite athletes tend to accumulate greater T@v\(\text{VO}_{2\text{max}}\) per session at some point of the season. In recreationally trained cyclists (v\(\text{VO}_{2\text{max}}\) = 52 mL/min/kg),

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Seiler et al. showed that larger volumes of HIT performed at a lower intensity (i.e. $4 \times 8\ 	ext{min} = 32\ 	ext{min}$ at 90% $\text{HR}_{\text{max}}$) may be more effective than more traditional HIT sessions (e.g. $4 \times 4\ 	ext{min}$) [176]. Further research examining the influence of these particular sessions in more highly trained athletes are, however, required to confirm these findings.

3.1.2 $\dot{V}O_2$ Responses to HIT with Short Intervals

For short interval HIT runs to exhaustion, $T@\dot{V}O_2\text{max}$ is largely correlated with total exercise time (i.e. time to exhaustion) [14]. Hence, the first approach to maximizing $T@\dot{V}O_2\text{max}$ during such sessions should be to focus on the most effective adjustments to work/relief intervals (intensity and duration) that increase time to exhaustion. In practice, however, coaches do not prescribe HIT sessions to exhaustion; they prescribe a series or set of HIT [50, 128, 177, 178]. In this context, it is important to consider the strategies needed to maximize $T@\dot{V}O_2\text{max}$ within a given time period, or to define ‘time-efficient’ HIT formats with respect to the $T@\dot{V}O_2\text{max}$/exercise time ratio (i.e. $T@\dot{V}O_2\text{max}$ in relation to the total duration of the HIT session, warm-up excluded).

3.1.2.1 Effect of Work Interval Intensity on $T@\dot{V}O_2\text{max}$

Billat et al. [23] were the first to show the effect of exercise intensity on $T@\dot{V}O_2\text{max}$ during HIT with short intervals ($15\ s/15\ s$) in a group of senior (average age: 52 years) distance runners ($\dot{V}O_2\text{max} = 15.9 \pm 1.8\ \text{km/h}$). While the concurrent manipulation of the relief interval intensity (60–80 % of $\dot{V}O_2\text{max}$, to maintain an average HIT intensity of 85 %) might partially have influenced the $\dot{V}O_2$ responses, the authors did show that increasing work interval intensity from 90 % to 100 % of $\dot{V}O_2\text{max}$ was associated with a ‘small’ improvement in the $T@\dot{V}O_2\text{max}$/exercise time ratio (81 % vs. 68 %, ES = +0.5). However, the $T@\dot{V}O_2\text{max}$/exercise time ratio (85 %) was not substantially greater using a work interval fixed at 110 compared with 100 % of $\dot{V}O_2\text{max}$ (ES = +0.2). Using a fixed relief interval intensity (Fig. 7a, [117, 177, 179]), increasing work intensity from 100 % to 110 % of $\dot{V}O_2\text{max}$ during a 30 s/30 s format in trained young runners ($\dot{V}O_2\text{max} = 17.7 \pm 0.9\ \text{km/h}$) induced a ‘moderate’ increase in the $T@\dot{V}O_2\text{max}$/exercise time ratio (ES = +0.6), despite ‘very large’ and ‘moderate’ reductions in time to exhaustion (ES = −4.4) and $T@\dot{V}O_2\text{max}$ (ES = −0.7), respectively [179]. A slight increase in work intensity from 100 % to 105 % of $\dot{V}O_2\text{max}$ during a 30 s/30 s HIT format in well trained triathletes ($\dot{V}O_2\text{max} = 19.8 \pm 0.93\ \text{km/h}$) was associated with a ‘large’ improvement in the $T@\dot{V}O_2\text{max}$/exercise time ratio (ES = +1.2) [177]. The twofold magnitude difference in Millet et al. [177] compared with Thevenet et al.’s study [179] (ES: +1.2 vs. +0.6) is likely due to the fact that Millet et al.’s runs were not performed to exhaustion, but implemented with pre-determined sets. It is therefore possible that if the runs at 100 % had been performed to exhaustion [177], this would have compensated for the lower efficiency of the protocol and decreased the difference in $T@\dot{V}O_2\text{max}$ observed. Similarly, increasing the work intensity from 110 % to 120 % of $v\dot{V}O_2\text{max}$ during a 15 s/15 s format in physical education students ($\dot{V}O_2\text{max} = 16.7 \pm 1.3\ \text{km/h}$) lead to a ‘large’ improvement in the $T@\dot{V}O_2\text{max}$/exercise time ratio (ES = +1.8) [117]. Interestingly, in the study by Millet et al. [177], individual improvements in $T@\dot{V}O_2$ with the increase in work intensity were inversely correlated with the athletes’ primary time constant for $\dot{V}O_2$ kinetics at exercise onset ($r = 0.91;\ 90\ \%\ CI\ 0.61, 0.98$), suggesting that the time constant could be an important variable to consider when selecting HIT variables [116, 177]. Practically speaking, this data implies that coaches should programme HIT at slightly greater exercise intensities for athletes presenting with slow $\dot{V}O_2$ kinetics (i.e. older/less trained [141]), or for athletes exercising on a bike [140]. However, since increasing exercise intensity has other implications (e.g. greater anaerobic energy contribution, higher neuromuscular load, see Part II), such programming manipulations need to use a cost/benefit approach.

With respect to the use of very-high-exercise intensities (>102/120 % $V_{\text{FTV}}\dot{v}\dot{V}O_2\text{max}$) for HIT, while the $T@\dot{V}O_2\text{max}$/exercise time ratio is high (81 % and 77 % at 130 % and 140 % of $\dot{V}O_2\text{max}$, respectively), exercise capacity is typically impaired and, hence, total $T@\dot{V}O_2\text{max}$ for a given HIT series is usually low [117] (i.e. 5 min 47 s at 120 % $v\dot{V}O_2\text{max}$ [117]). Nevertheless, the use of repeated sets of such training can allow the accumulation of a sufficient $T@\dot{V}O_2\text{max}$. Additionally, well trained athletes are generally able to perform HIT at this intensity for longer periods (i.e. >8 min [43, 50, 95, 180], especially when $V_{\text{FTV}}$, instead of $v\dot{V}O_2\text{max}$, is used [94]). To conclude, it appears that during HIT that involves short work intervals, selection of a work bout intensity that ranges between 100 % and 120 % of $\dot{V}O_2\text{max}$ (>89 % and 105 % of $V_{\text{FTV}}$) may be optimal.

3.1.2.2 Effect of Work Interval Duration on $T@\dot{V}O_2\text{max}$

The effect of work interval duration on systemic $\dot{V}O_2$ responses during HIT involving repeated short intervals was one of the first parameters examined in the HIT literature [11, 12]. Surprisingly, there is little data available on repeated efforts lasting less than 15 s, despite the
common approach used by coaches (e.g. 10 s/10 s, 10 s/20 s) [181, 182]. During very short runs (<10 s), ATP requirements in working muscle are met predominantly by oxidative phosphorylation, with more than 50% of the O2 used derived from oxyhemoglobin stores [11]. During the recovery periods, oxymyoglobin stores are rapidly restored and then available for the following interval [11]. As a result, the cardiopulmonary responses of such efforts are relatively low [183], unless exercise intensity is set at a very high level (as detailed in Sect. 3.1.4) and/or relief intervals are short/intense enough so that they limit complete myoglobin resaturation. Therefore, in the context of HIT involving short intervals (100–120% vVO2max or 89/105% V̇O₂FT), work intervals ≥10 s appears to be required to elicit high V̇O₂ responses. Surprisingly, the specific effect of work interval duration, using a fixed work/rest ratio in the same group of subjects, has not been investigated thus far; whether, for example, a 15 s/15 s HIT session enables a greater T@VO2max/exercise time ratio than a 30 s/30 s session is unknown.

What is known of course is that prolonging exercise duration increases the relative aerobic energy requirements [184]. Increasing the work interval duration, while keeping work relief intervals constant, also increases T@VO2max (Fig. 7b, [128, 185, 186]). For example, extending work interval duration from 30 s to 60 s using a fixed-relief duration of 30 s in well trained triathletes (vVO2max = 19.9 ± 0.9 km/h) induced ‘very large’ increases in T@VO2max (9 vs. 1.5 min, ES = +2.4), despite a shorter total session time (28 vs. 34 min, ES = −0.9; change in the T@VO2max/exercise ratio, ES = +2.8) [128]. Similarly, in wrestlers (vVO2max = 16.3 ± 1.1 km/h), increasing running work interval duration from 15 s to 30 s lead to ‘very large’ increase in T@VO2max (4 vs. 0 min, ES = 2.9); [185] a further increase in the interval duration to 60 s extended T@VO2max to 5.5 min (ES = 0.5 vs. the 30-s condition). Considering the importance of VO2 kinetics for extending T@VO2max [177], these data suggest that longer work intervals (e.g. 30 s/30 s vs. 15 s/15 s) are preferred for individuals with slow VO2 kinetics (i.e. older/less trained [141]), or for exercising on a bike [140].

### 3.1.2.3 Characteristics of the Relief Interval and T@VO2max

The intensity of the relief interval also plays a major role in the VO2 response during HIT involving short intervals, since it affects both the actual VO2 during the sets and exercise capacity (and, hence, indirectly time to exhaustion and T@VO2max; Fig. 7c, [164, 187, 188]). Compared with passive recovery, runs to exhaustion...
involving active recovery are consistently reported to be 40–80 % shorter [164, 187–190]. Therefore, when considering runs to exhaustion during 15 s/15 s exercises, the absolute T@VO2max might not differ between active and passive recovery conditions [190] (ES = −0.3), but the T@VO2max/exercise time ratio is substantially greater when active recovery is implemented (ES = +0.9); a factor of obvious importance when implementing pre-determined sets of HIT [50, 128, 178]. During a 30 s/30 s exercise model, compared with passive recovery, recovery intensities of 50 % and 67 % of vVO2max were associated with ‘small’ and ‘very large’ improvements in T@VO2max (ES = +0.4 and +0.1, respectively) and the T@VO2max/ exercise time ratio (ES = +2.3 and +4.1, respectively) [164, 188]. Increasing the recovery intensity to 84 % reduced ‘moderately’ T@VO2max (ES = −0.6), but increased ‘very largely’ the T@VO2max/exercise time ratio (ES = +3.4). Taken together, these studies suggest that, for the short HIT formats examined thus far, relief interval intensities around ≈70 % vVO2max should be recommended to increase both T@VO2max and the T@VO2max/ exercise time ratio [23]. The fact that active recovery had a likely greater impact on T@VO2max during the 30 s/30 s [164, 188] compared with the 15 s/15 s [190] exercise model is related to the fact that VO2 reaches lower values during 30 s of passive rest, which directly affects VO2 levels during the following effort. For this reason, we recommend programming passive recovery <15–20 s for non-endurance sport athletes not familiar with performing active recovery, and/or performing active recovery during longer-relief interval durations (≥20 s). In general, the characteristic of the relief interval intensity can be adjusted in alignment with the work intensity, with higher-relief interval intensities used for lower-work interval intensities [23], and lower-relief exercise intensities used for higher-work interval intensities and durations [117, 177, 179].

3.1.2.4 Series Duration, Sets and T@VO2max Dividing HIT sessions into sets has consistently been shown to reduce the total T@VO2max [50, 128, 178]. For example, in endurance-trained young runners (vVO2max = 17.7 ± 0.3 km/h), performing 4-min recoveries (30 s rest, 3 min at 50 % vVO2max, 30 s rest) every 6 repetitions (30 s/30 s) was associated with a ‘moderately’ lower T@VO2max (ES = −0.8) despite ‘very large’ increases in time to exhaustion (ES = +4.3); the T@VO2max/exercise time ratio was therefore ‘very largely’ reduced (ES = −2.3) [178]. This is likely related to the time athletes needed to return to high VO2 levels after each recovery period, irrespective of the active recovery used. While it could be advised to consistently recommend HIT runs to exhaustion to optimize T@VO2max, this would likely be challenging, psychologically speaking, for both coaches and athletes alike; this is likely why HIT sessions to exhaustion are not often practiced by athletes.

In practice, the number of intervals programmed should be related to the goals of the session (total ‘load’ or total T@VO2max expected), as well as to the time needed to reach VO2max and the estimated T@VO2max/exercise time ratio of the session. The time needed to reach VO2max during different work- and relief-interval intensities involving short HIT (30 s/30 s) was recently examined in young endurance-trained athletes [164, 179, 188]. Not surprisingly, these studies showed shorter time needed to reach VO2max values for work intensities ≥105 % vVO2max and relief intensities ≥60 % vVO2max. Conversely, using slightly lower work- and/or relief-interval intensities (i.e. work: 100 % and relief: 50 % vVO2max) the runners needed more than 7 min to reach VO2max. Despite a lack of statistical differences [164, 179, 188], all ES between the different work/relief ratios examined were ‘small’ to ‘very large’. In the field then, time needed to reach VO2max might be accelerated by manipulating HIT variables during the first repetitions of the session, i.e. using more intense work- and/or relief-interval intensities during the first two to three intervals, or using longer work intervals and/or shorter relief intervals.

If we consider that a goal T@VO2max of ≈10 min per session is appropriate to elicit important cardiopulmonary adaptations (Sect. 3.1.1.5), athletes should expect to exercise for a total of 30 min using a 30 s [110 % vVO2max]/30 s [50 % vVO2max] format, since the T@VO2max/total exercise time ratio is approximately 30 % (Fig. 7). Since it is unrealistic to perform a single 30-min session, it is possible for it to be broken into three sets of 10–12 min (adding 1–2 min per set to compensate for the time needed to regain VO2max during the second and third set). Such a session is typical to that used regularly by elite distance runners in the field. A lower volume (shorter series or less sets) may be used for other sports (i.e. in team sports, a T@VO2max of 5–7 min is likely sufficient [116]) and/or for maintenance during unloading or recovery periods in an endurance athlete’s programme. In elite handball, for example, 2 × (20 × 10 s [110 % Vmax]/20 s [0]) is common practice, and might enable players to spend ≈7 min at VO2max (considering a T@VO2max/exercise time ratio of 35 %; Buchheit M, unpublished data). In football (soccer), HIT sessions such as 2 × (12–15 × 15 s [120 % Vmax]/ 15 s [0]) are often implemented [95], which corresponds to ≈6 min at VO2max (14 min with a T@VO2max/exercise time ratio of ≈45 % [190]).

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3.1.3 Short versus Long Intervals and T@VO$_{2\max}$

A direct comparison between long and short HIT sessions, with respect to T@VO$_{2\max}$, has only been reported twice in highly-trained athletes. Gajer et al. [174] compared T@VO$_{2\max}$ between 6 x 600 m (track session, 102 % vVO$_{2\max}$, ran in ~1 min 40 s) and 10 repetitions of a 30 s/30 s HIT session (work/relief intensity: 105/50 % vVO$_{2\max}$) in elite middle-distance runners (vVO$_{2\max}$ = 21.2 ± 0.6 km/h). While VO$_2$ reached 105 % VO$_{2\max}$ during the track session, VO$_{2\max}$ was not actually attained during the 30 s/30 s session. If the track session is considered as the ‘reference’ session (T@VO$_{2\max}$/exercise time ratio: 44 %), T@VO$_{2\max}$ was ‘very largely’ lower during the 30 s/30 s interval (10 %, ES = ~2.6). Similarly, Millet et al. [128] showed that performing 2 min/2 min intervals enabled triathletes to attain a ‘very largely’ longer T@VO$_{2\max}$ compared with a 30 s/30 s session (ES = +2.2, T@VO$_{2\max}$/exercise time ratio = +2.2). Long intervals were however ‘moderately’ less ‘efficient’ than a 60 s/30 s effort model (T@VO$_{2\max}$/exercise time ratio, ES = −0.8) [128]. Taken together, these data suggest that long intervals and/or short intervals with a work/relief ratio >1 should be preferred due to the greater T@VO$_{2\max}$/exercise time ratio.

3.1.4 VO$_2$ Responses to Repeated-Sprint Sequences

Compared with the extensive data available on cardiorespiratory responses to long and short HIT, relatively little has been presented on the acute responses to RSS. An RSS is generally defined as the repetition of >two short (≤10 s) all-out sprints interspersed with a short recovery period (<60 s) [191]. Early in the 1990s, Balsom et al. [13] demonstrated that RSS were aerobically demanding (i.e. >65 % VO$_{2\max}$). In addition, Dupont et al. have shown that footballers can reach VO$_{2\max}$ during repeated sprinting [192]. To our knowledge, however, T@VO$_{2\max}$ during RSS has not been reported. For the purpose of the present review, we have reanalysed data from previous studies [30, 158, 193, 194] to provide T@VO$_{2\max}$ values for several forms of RSS (Fig. 8, upper panel [13, 30, 158, 192–195]). When manipulating key variables already described (Fig. 2 [35]), VO$_{2\max}$ is often reached and sustained for 10–40 % of the entire RSS duration (i.e. 10–60 s; Fig. 8 a). If RSS are repeated two to three times per session, as is often done in practice [180, 196, 197], the majority of athletes may spend up to 2–3 min at VO$_{2\max}$ during the repeated sprints. To increase T@VO$_{2\max}$ during an RSS, it appears that sprints/efforts should last at least 4 s, and that the recovery should be active and less than 20 s (Fig. 8, lower panel [13, 30, 158, 192–195]). The introduction of jumps following the sprints [193], and/or changes in direction [194], are also of interest, since these may increase systemic O$_2$ demand without the need for increasing sprint distance, which could increase muscular load and/or injury risk (see review Part II). Nevertheless, with very short passive recovery periods (i.e. 17 s), some athletes can reach VO$_{2\max}$ by repeating 3 s sprints only (15 m). It is worth noting, however, that during all RSS examined here (Fig. 8, except for Dupont et al’s. study [192]), a number of players did not reach VO$_{2\max}$ and T@VO$_{2\max}$ showed high interindividual variations (CV = 30–100 %). More precisely, when considering the four different forms of RSS performed by the same group of 13 athletes [193, 194], it was observed that six (45 %) of them reached VO$_{2\max}$ on four occasions, one (8 %) on three, four (31 %) on two, with two (15 %) never reaching VO$_{2\max}$ during any of the RSS. When the data from the four RSS were pooled, the number of times that VO$_{2\max}$ was reached was inversely related to VO$_{2\max}$ (r = −0.61, 90 % CL −0.84, −0.19). Similarly, the total T@VO$_{2\max}$ over the four different RSS was inversely correlated with VO$_{2\max}$ (r = −0.55; 90 % CL −0.85, 0.00). There was, however, no relationship between the number of times that VO$_{2\max}$ was reached or the T@VO$_{2\max}$ and VO$_2$ kinetics at exercise onset, as measured during submaximal exercise [144]. These data show that, with respect to T@VO$_{2\max}$ using RSS may be questionable to apply in some athletes, especially those of high fitness.

3.1.5 VO$_2$ Responses to Sprint Interval Sessions

The important research showing the benefits of SIT [126], notwithstanding, there is, to date, few data available showing the acute physiological responses to typical SIT sessions that might be implemented in practice. Tabata et al. [198] showed that VO$_{2\max}$ was not reached (peak of 87 % VO$_{2\max}$) during repeated 30 s cycling efforts (200 % of pVO$_{2\max}$ and therefore not actually ‘all-out’) interspersed by 2-min passive recovery. In contrast, we recently showed [142] that during a ‘true’ all-out SIT session, most subjects reached values close to (or above) 90 % of their VO$_{2\max}$ and HR. Nevertheless, T@VO$_{2\max}$ was only 22 s on average (range 0–60 s, with two subjects showing no values >90 % VO$_{2\max}$) [142], and VO$_{2\max}$ was reached by five (50 %) subjects only. These important individual VO$_2$ responses to SIT sessions were partly explained by variations in cardiorespiratory fitness (i.e. there was a negative correlation between T@VO$_{2\max}$ and both VO$_{2\max}$ (r = −0.68; 90 % CL −0.90, −0.20) and VO$_2$ kinetics at
noting that although pulmonary VO$_2$ is not high during SIT, muscle O$_2$ demand likely is, especially as the number of sprint repetitions increase. It has been shown that there is a progressive shift in energy metabolism during a SIT session, with a greater reliance on oxidative metabolism when sprints are repeated [199, 200]. Along these same lines, muscle deoxygenation levels and post-sprint reoxygenation rates have been shown to become lower and slower, respectively, with increasing sprint repetition number. This response implies a greater O$_2$ demand in the muscle with increasing sprint repetition (since O$_2$ delivery is likely improved with exercise-induced hyperaemia) [142].

### 3.1.6 Summary

In this section of the review, we have highlighted the VO$_2$ responses to various forms of HIT. It appears that most HIT formats, when properly manipulated, can enable athletes to reach VO$_2$max. However, important between-athlete and between-HIT format differences exist with respect to T@VO$_2$max. RSS and SIT sessions allow for a limited T@VO$_2$max compared with HIT that involve long and short intervals. Combined, data from high-level athletes [128, 174] suggest that long intervals and/or short intervals with a work/relief ratio $>$1 should enable a greater T@VO$_2$max/exercise time ratio during HIT sessions. The methods of maximizing long-term VO$_2$max development and performance adaptations using different forms of HIT sessions that involve varying quantities of T@VO$_2$max, as well as the most efficient way of accumulating a given T@VO$_2$max in an HIT session (i.e. intermittently vs. continuously), is still to be determined.

### 3.2 Cardiac Response with HIT and Repeated-Sprint Efforts

Due to the varying temporal aspects [70] and possible dissociation between VO$_2$ and cardiac output (Qc) during intense exercise [201, 202], T@VO$_2$max might not be the sole criteria of importance for examining when assessing the cardiopulmonary response of a given HIT session. Since reaching and maintaining an elevated cardiac filling is believed to be necessary for improving maximal cardiac function [58, 59, 203], training at the intensity associated with maximal SV may be important [201]. Defining this key intensity, however, remains difficult, since this requires the continuous monitoring of SV during exercise (e.g. [25–27, 201, 204]). Interestingly, whether SV is maximal at v/VO$_2$max, or prior to their occurrences, is still debated [205–207]. SV behaviour during an incremental test is
likely protocol-dependent [202] and affected by training status (e.g. ventricular filling partly depends on blood volume, which tends to be higher in trained athletes) [206], although this is not always the case [207]. In addition, the nature of exercise, i.e. constant power vs. incremental vs. intermittent, as well as body position (more supine during rowing or swimming vs. more upright during running and cycling), might also affect the SV reached and maintained throughout the exercise bout. In fact, there is limited data on cardiac function during exercises resembling those prescribed during field-based HIT sessions, i.e. constant-power bouts at high intensity. In these studies, SV reached maximal values within 1 min [26], 2 min [24, 25, 204] and 4 min [27], and then decreased [24, 26, 204] or remained stable [25, 27] prior to fatigue. Inconsistencies in exercise intensities, individual training background and particular haemodynamic behaviours (e.g. presence of a HR deflection at high intensities [208]), as well as methodological considerations in the measurement of SV may explain these differences [205–207]. As discussed in Sect. 2.2, alternating work and rest periods during HIT with short intervals might also induce variations in the action of the venous muscle pump, which can, in turn, limit the maintenance of a high SV [60].

Following the beliefs of German coach, Woldemar Gerschler, in the 1930s, Cumming reported, in 1972, that maximal SV values were reached during the exercise recovery period, and not during exercise, irrespective of the exercise intensity [209]. Although these results were obtained during supine exercise in untrained patients, and despite contradictory claims [210], they contributed to the widespread belief that the repeated recovery periods and their associated high SV accounted for the effectiveness of HIT on cardiocirculatory function [211]. In partial support of this, Takahashi et al. [212] also reported in untrained males that during the first 80 s of an active recovery (20 % \( \dot{V}O_{2\max} \)), SV values were 10 % greater than during a preceding submaximal cycling exercise (60 % \( \dot{V}O_{2\max} \)). Surprisingly, these particular and still hypothetical changes in SV during recovery had never before been examined during typical HIT sessions in athletes. We recently collected haemodynamic data in well trained cyclists that partly confirmed Cumming’s findings (Buchheit M, et al., unpublished data, Fig. 9). Irrespective of the exercise, i.e. incremental test, 3 min at p\( \dot{V}O_{2\max} \) or repeated 15-s sprints (30 % of the anaerobic power reserve, APR), the SV of a well trained cyclist (peak power output = 450 W, \( \dot{V}O_{2\max} = 69 \) ml/min/kg, training volume = 10 h/week) showed its highest values consistently during the recovery periods (upright position on the bike). While we acknowledge the limitations inherent to the impedance method used (PhysioFlow, Manaetac, France [213, 214]), and while further analysis on a greater number of subjects is needed, these preliminary data lend support to the belief that despite its supramaximal nature, HIT sessions might trigger cardiocirculatory adaptation via cardiovascular adjustments occurring specifically during the recovery periods. Take for example an HIT session involving three sets of eight repetitions of a 15 s sprint (30 % APR) interspersed with 45 s of passive recovery (long enough for peak SV to be reached). Such a format would allow such athletes to maintain their peak SV for 24 × 20 s = 480 s, which is similar to what can be sustained during a constant-power exercise performed to exhaustion [25]. Interestingly, Fontana et al. [215] also observed, using a rebreathing method in untrained men, ‘largely’ greater SV values at the end of a 30 s all-out sprint compared with an incremental test to exhaustion (127 ± 37 vs. 94 ± 15 ml, ES = +1.3). HR\( \text{max} \) was nevertheless ‘very largely’ lower (149 ± 26 vs. 190 ± 12 beats/min, ES = −2.2), so there was no substantial difference in maximal cardiac output (Qc\( \text{max} \)) [18.2 ± 3.3 vs. 17.9 ± 2.6 L/min, ES = −0.1].

To conclude, the optimal nature and intensity of exercise needed to produce the greatest SV adaptations is not known. In acquiring the answer to this question, one needs to take into account individual characteristics, such as fitness level, training status and various individual haemodynamic behaviours to different exercise modes. In a practical way, on the basis of the limited data available, it might be recommended to prescribe a variety of different training methods to gain the adaptation advantages of each exercise format. HIT sessions, including near-to-maximal long intervals with long recovery durations (e.g. >3–4 min/2 min) might allow athletes to reach a high SV during the work (and possibly the rest intervals). Along these same lines, 4-min intervals ≈90–95 % v\( p \dot{V}O_{2\max} \) appear to be receiving the greatest interest to improve cardiopulmonary function (e.g. [46, 59, 216]). Alternatively, repeated short supramaximal work intervals (e.g. 15–30 s) with long recovery periods (>45 s) might also be effective at reaching high values both during exercise [215] and possibly, in recovery (Fig. 9). However, whether Qc\( \text{max} \) adaptations are comparable following long- and short-interval sessions (i.e. continuous vs. intermittent), or whether achieving a certain quantity of time at Qc\( \text{max} \) (T@Qc\( \text{max} \)) is needed to maximize its adaptation, is still unknown. In the only longitudinal study to date comparing the effect of short versus long HIT on maximal cardiovascular function in university students (\( \dot{V}O_{2\max} : 55–60 \) ml/min/kg) [59], there was a ‘small’ trend for greater improvement in Qc\( \text{max} \) for the long interval protocol (ES = +1 vs. +0.7 for 4 × 4 min vs. 15/15, respectively). It is worth noting that Seiler et al. [176] showed, in recreational cyclists (\( \dot{V}O_{2\max} : 52 \) ml/min/kg), that accumulating 32 min of work at 90 % HR\( \text{max} \) may
actually induce greater adaptive gains than 16 min of work at ~95% $HR_{\text{max}}$ [176]. While $SV$ was not measured, these results contrast with the idea that exercise intensity directly determines the training responses [59]. Rather, they show that both exercise intensity and accumulated duration of interval training may act in an integrated way to stimulate physiological adaptations in this population [176]. In this latter case [176], the decrease in exercise intensity may have allowed for a greater T@Qc_{max} (or near Qc_{max}), and, in turn, a greater adaptation. Whether similar results would be observed in highly trained athletes who are more likely to require greater levels of exercise stress for further adaptations, is still unknown. Finally, since T@Qc_{max} has been shown to be largely correlated with time to exhaustion during severe exercise ($r$ ranging from 0.79; 90% CL 0.45, 0.93 to $r$ 0.98; 90% CL 0.94, 0.99) [25], pacing strategies that can increase time to exhaustion but that sustain a high cardiorespiratory demand may also be of interest. For instance, adjusting work intensity based on VO2 responses (constant-VO2 exercise at 77% VO2_{max} on average) instead of power (constant-power exercise at 87% pVO2_{max}) led to ‘moderate’ increases in time to exhaustion (20 min ± 10 min vs. 15 min ± 5 min, ES = +1.0) and, in turn, T@Qc_{max} (16 min ± 8 min vs. 14 min ± 4 min, ES = +0.9) [25].

**Fig. 9** a VO2, HR, SV and muscle oxygenation (TSI) during an incremental test followed by two sets of three supramaximal 15-s sprints (35% APR); b 5-min bout at 50% of pVO2_{max} immediately followed by 3 min at pVO2_{max}; and c the early phase of an HIT session (i.e first four exercise bouts (15-s [35% APR]/45 s [passive]); in a well trained cyclist. Note the reductions in SV for intensities above >50% of VO2_{max} during both the incremental and constant power tests, which is associated with a greater muscle deoxygenation during the incremental test. In contrast, maximal SV values are consistently observed during the post-exercise periods, either following incremental, maximal or supramaximal exercises. APR anaerobic power reserve, HIT high-intensity interval training, HR heart rate, VO2_{max} maximal oxygen uptake, p VO2_{max}, minimal power associated with VO2_{max}, SV stroke volume, TSI tissue saturation index.

**4 Conclusions**

In Part I of this review, the different aspects of HIT programming have been discussed with respect to T@VO2_{max} and cardiopulmonary function. Important between-athlete and between-HIT format differences exist, so that precise recommendations are difficult to offer. Most HIT formats, if properly manipulated, can enable athletes to reach VO2_{max} but SS and SIT sessions allow limited T@VO2_{max} compared with HIT sessions involving long and short intervals. The VO2 responses during RSS and SIT appear to be fitness-dependent, with the fitter athletes less able to reach VO2_{max} during such training. Based on the current review, the following general recommendations can be made:

1. To individualize exercise intensity and target specific acute physiological responses (Fig. 1), v/pVO2_{max} and ASR/APR or V_{HIT} are likely the more accurate references needed to design HIT with long (≥1-2 min) and short (≤45 s) intervals, respectively. For run-based HIT sessions, compared with the ASR, $V_{HIT}$ integrates between-effort recovery abilities and COD capacities that make $V_{HIT}$ especially relevant for programming short, supramaximal intermittent runs.
performed with COD, as implemented in the majority of team and racket sports.

2. Especially in well-trained athletes that perform exercises involving large muscle groups, and assuming the accumulation of T\@VO_{2max} may maximize the training stimulus to improving performance, we recommend long- and short-bout HIT with a work/relief ratio >1 (see Part II, Table I for practical programming suggestions). Additionally:

a. There should be little delay between the warm-up and the start of the HIIT session so that the time needed to reach VO_{2max} is accelerated. Warm-up intensity can be ≤60–70 % v/pVO_{2max}, or game-based (moderate intensity) for team and racket sport athletes.

b. Total session volume should enable athletes to spend between ≈5 (team and racket sports) and ≈10 (endurance sports) min at VO_{2max}.

3. Until new evidence is provided, the importance of continuous versus repeated ventricular filling at high rates for developing cardiovascular adaptations is not known. Near-to-maximal and prolonged work intervals currently appear to be the preferred HIT option (i.e. >4 min at 90–95 % v/pVO_{2max}, with likely decreasing external load with increasing fatigue to prolong T\@Qc_{max}).

5 Perspective

Further research is required to specify the acute cardiovascular responses to HIT/RST/SIT in particular populations such as youth and female athletes, as well as the influence that training status and cardiorespiratory fitness have on these responses. Further research is also needed to improve our understanding of how to optimally manipulate HIT variables, in particular, environmental conditions (e.g. altitude [21], heat [217]), where ‘typical’ HIT sessions, as suggested for programming in the present review, cannot be performed. The impact of time of day, timing within a session, and external training contents should also be examined, as typically most studies are conducted with ‘fresh’ participants in controlled environments, while in practice, HIIT sessions are often performed in a state of accumulated fatigue (end of a team-sport session or in the afternoon following an exhaustive morning training session). Understanding the physiological responses to technical/tactical training sessions is also likely an important aspect of successful training in team sport athletes, so that the optimal HIT sessions can be programmed as supplemental sessions (i.e. how does one “best solve the programming puzzle”), while adding what is ‘missed’ during the technical/tactical sessions [151], since physiological and performance adaptations have been shown to occur in relation to the accumulated training load completed at high intensities [218]). Finally, since in team sports improvements in physical fitness might not have a similar impact on match running performance for all players (influence of playing positions, systems of play, individual playing styles) [63, 98, 219, 220], the implementation of HIT sessions should be individualized and considered using a cost-benefit approach. As will be discussed in Part II, consideration for other important aspects of HIT programming, such as glycolytic anaerobic energy contribution, neuromuscular load and musculoskeletal strain, should also be considered. Further studies are also needed to examine the long-term adaptations to all forms of HIT/repeated all-out efforts presented in the present review with respect to gender, age and training status/background.

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