VO2max Test of Unhealthy Participants

Subjects: Sport Sciences

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Maximal oxygen uptake (VO2max) is strongly associated with endurance performance as well as health risk. Despite the fact that VO2max has been measured in exercise physiology for over a century, robust procedures to ensure that VO2max is attained at the end of graded exercise testing (GXT) do not exist. This shortcoming led to development of an additional bout referred to as a verification test (VER) completed after incremental exercise or on the following day.

verification testing | maximal oxygen uptake | unhealthy adults | graded exercise testing | VO2max criteria

1. Introduction

Maximal oxygen uptake (VO_2max) as determined by the Fick Equation represents the maximal ability of the cardiovascular system to transport oxygen and the capacity of the periphery to extract oxygen to support aerobic metabolism. It is apparent that VO_2max is related to endurance performance and, more importantly, premature mortality [1]. Because of this link between VO_2max and health status, the American College of Sports Medicine [2] recommends 150 min/week of moderate intensity continuous exercise or 75 min/week of vigorous exercise to enhance fitness and improve overall health status, although attainment of this guideline in U. S. adults is relatively low [3].

Despite the fact that VO_2max has been measured in laboratory and clinical settings for a century, there is no standardized exercise testing protocol to assess it as the specific work rate increment, stage duration, and gas exchange sampling interval vary across studies. In addition, there is no robust approach to ensure that VO_2max is attained at the end of incremental exercise which is problematic when this value is used to prescribe exercise, assess training responsiveness, or describe health status. In turn, relying on an imprecise estimate of VO_2max can have negative effects upon the accuracy of these applications which can change the course of decision making made by practitioners or scientists regarding client health. Various primary (oxygen plateau) and secondary criteria (maximal values of heart rate, respiratory exchange ratio, rating of perceived exertion, and blood lactate concentration) are widely used in this capacity, yet each has its limitations (for additional information on this, please consult Schaun et al. [4]) that may make them ineffective in ensuring that VO_2max is actually attained by each participant.

Implementation of a second exercise test completed after the incremental test was first identified by Thoden et al. [5] in active adults who required an ‘exhaustive test’ to be performed after the incremental protocol. Later work [6][7] showed that completion of this subsequent higher intensity bout (called the verification test (VER)), performed a few minutes or up to 1 week after the incremental exercise bout, led to similar mean estimates of VO_2max, thus confirming a plateau in oxygen uptake and, in turn, attainment of VO_2max. For example, in 16 distance runners, data [8] showed that 26 of 32 VO_2max tests performed on a treadmill reveal similar (≤2% different) estimates of VO_2max between ramp and subsequent verification testing. In seven healthy men, Rossiter et al. [9] demonstrated that VER at 95 or 105%of peak power output (PPO) performed 5 min after ramp exercise elicits similar values of VO_2max, leading these authors to recommend either protocol as a suitable way to confirm VO_2max attainment. Overall, these data show that VER is a robust procedure to confirm attainment of VO_2max in healthy active adults.

Despite these data, a valid concern of VER is that its supramaximal effort would be inappropriate for those who are inactive or at risk for chronic disease who lack the exercise capacity due to aging, presence of comorbidities, or desire to sustain such demanding efforts long enough to allow VO_2 to attain a maximal value. However, results from inactive adults [10], older adults [11], and those with obesity [12][13][14] demonstrate that it is well-tolerated and feasible in these populations and leads to similar estimates of VO_2max as the ramp test. In addition, data show its efficacy to confirm attainment of VO_2max in adults with metabolic syndrome [15] as well as heart failure [16]. Recent data also show that implementing VER reveals more precise determinants of increases in VO_2max in response to high intensity interval training in adults with metabolic syndrome compared to graded exercise testing [17]. So, similar to healthy adults, use of VER seems warranted to confirm attainment of ‘true’ VO_2max in persons with chronic disease.

A recent systematic review [18] summarized data concerning efficacy of VER in healthy participants and concluded that this is a robust approach to confirm the value acquired from incremental exercise. However, having a more accurate estimate of ‘true’ VO_2max in this active population may not be that important as their cardiorespiratory fitness is superior, leading to enhanced health status versus less fit populations. In response to exercise training, an increase in VO_2max as low as 1.5 mL/kg/min has been identified as being clinically significant in persons with chronic disease [19]. Thus, in persons having low VO_2max and, in turn, diminished health status, any small inaccuracies in VO_2max assessment may elicit different responses to training and/or inaccurate diagnoses that may modify choice of various treatment options implemented to improve individual health status. In addition, VO_2max is frequently measured as a primary outcome in exercise training studies due to its strong relationship with health status [1]. Moreno-Cabanas et al. [17] concluded that ramp testing misrepresents the training-induced change in VO_2max in a majority of individuals with metabolic syndrome, and they emphasized the necessity of VER to better represent the VO_2max response to training. However, to our knowledge, no review article has summarized efficacy of VER to confirm VO_2max incidence in unhealthy participants. Some studies show that VER leads to similar estimates of VO_2max versus graded exercise testing, whereas others show significantly higher VO_2max when VER is performed. These equivocal findings may cloud judgment as to whether this additional test should be performed to elicit a ‘true’ VO_2max and merit development of a review article to provide a thorough overview of feasibility of VER in clinical populations.

2. Methods Used to Assess VO_2max during Incremental and Verification Testing

Table 1 denotes the methods used to assess VO_2max from graded exercise testing and the subsequent verification test. Fourteen studies utilized primary (VO_2 plateau) and secondary criteria (RERmax, HRmax, RPE, and/or blood lactate concentration) to verify attainment of VO_2max from GXT, although five studies did not report that any VO_2max criteria were used. Cycling was the modality used in 14 of 19 studies, with 1 study employing arm ergometry [20] and 4 studies using treadmill exercise in overweight to obese adults [12], adults with hypertension [21], athletes with spinal cord injury [22], and children with spina bifida [23]. The most widely used protocol to assess VO_2max during GXT was a traditional ramp test (*n* = 10 studies), although in nine studies, a step incremental test was used. Studies were characterized by various intervals between protocols, with durations as brief as four minutes to as long as a few hours between tests. Two studies required VER to be performed 24–48 h after completion of GXT.

Table 1. Methodological traits of exercise testing of studies included in this review.

Study	Exercise Mode	Traditional VO_{2max} Criteria Adopted	VO_{2max} Protocol	Recovery Phase Protocol	VER Protocol	VER vs. GXT Criteria
Arad et al. [22]	CE	VO_2 plateau; RER ≥ 1.10; ≥95% HRmax	RAMP 4 min unloaded cycling + 1 W/3 s for women 1 W/4 s for men	10 min active recovery at 25 W + 2–3 min passive	100% PPO	NR
Astorino et al. [9]	CE	NR	STEP 14 W/min for women 21 W/min for men and 5 W/20 s for women and 10 W/20 s for men	1–1.5 h or 24 h later	2-min WU at 28 W for women, 42 W for men followed by cycling at 105 or 115% PPO	NR
Astorino et al. [20]	ACE	VO_2 plateau using individual ΔVO_2 values for each participant	RAMP 5 min warm-up + 3 W/min for TETRA, 13 W/min for PARA, and 8–20 W/min for AB	10 min active recovery at 7 W	2 min at 7 W + arm cycling 105% PPO	NR
Astorino et al. [13]	CE	NR	RAMP 40 W for 2 min	10 min active	2 min WU at 20 W + cycling at	A conservative difference in

Study	Exercise Mode	Traditional VO_{2max} Criteria Adopted	VO_{2max} Protocol	Recovery Phase Protocol	VER Protocol	VER vs. GXT Criteria
			+ 20 W/min	recovery at 20 W	105% PPO	VO_2max between protocols <0.06 L/min was used to identify 'true' VO_2max
Bhammar et al. [24]	CE	RER ≥ 1.00, HR ≥ 90% of age-predicted HRmax	STEP 6 min at 40 W + initial WR of 20 W followed by 10–15 W/min	15 min of passive recovery	2 min WU at 20 W + cycling at 105% PPO	Measured VER VO_2max was considered higher than measured GXT VO_2max when difference between measured VER and GXT VO_2max was greater than the difference between predicted values
Bhammar et al. [25]	CE	HR > 85% age-predicted HRmax; RER > 1.15	STEP 40 W + 20 W/min for women 50 W + 25 W/min for men	15 min passive recovery	2 min WU at 30 W for women, 40 W for men + cycling at 105% PPO	VER-derived VO_2max was higher than incremental VO_2max when the difference between measured VER VO_2max and incremental VO_2max was greater than the difference between predicted VER and incremental VO_2max
Bowen et al. [15]	CE	BLa > 8 mM; HR within 10% of age-	RAMP 4 min at 10 W + 4–18 W/min	5 min active recovery at 10 W	4 min WU at 10 W + cycling at 95% PPO	NR

Study	Exercise Mode	Traditional VO_{2max} Criteria Adopted	VO_{2max} Protocol	Recovery Phase Protocol	VER Protocol	VER vs. GXT Criteria
		predicted HRmax; RPE > 18; RER > 1.00–1.15				
Causer et al. [26]	CE	VO_2 plateau; RPE > 9; RER > 1.03–1.05; Predicted VO_2peak, PPO, or HRpeak	RAMP 3 min at 20 W + 10–25 W/min	5 min cool-down at 20 W +10 min seated rest	3 min WU at 20 W + cycling at 110% PPO	Less than 9% difference between protocols
Dalleck et al. [10]	CE	RER > 1.0–1.15; HR within 10 b/min of age-predicted HRmax; VO_2 plateau	STEP2 min WU at 50 W + 10–15 W/min	60 min passive recovery	2 min WU at 50 W + cycling at 105% PPO	Less than 3% difference in VO_2max between tests
de Groot et al. [23]	TM	Heart rate = 95% (210–age); RER > 1.0; VO_2 plateau	STEP 2% grade + 2 km/h + 0.25% change in grade/min or 3 km/h + 0.50% change in grade per min	4 min passive recovery	110% peak speed	Difference in VO_2max between protocols >2.1 mL/kg/min
Leicht et al. [22]	TM	VO_2 plateau; RER > 1.05 BLa > 4.0 mM; HR > 85% age-predicted HRmax	STEP Constant speed at 1% grade and grade increased by 0.1–0.3%/min	5 min active recovery at 1 m/s at 1% grade	Same peak speed as GXT but supramaximal gradient (+0.6% for PARA and NON-SCI; +0.3% for TETRA)	NR
Mahoney et al. [27]	CE	NR	RAMP 5 min WU at 20	At least 2 days later	2 min rest + 5 min WU at 50	NR

Study	Exercise Mode	Traditional VO_{2max} Criteria Adopted	VO_{2max} Protocol	Recovery Phase Protocol	VER Protocol	VER vs. GXT Criteria
			W before power continuously increased that was individualized for each participant		W + cycling at 80–105% PPO	
Misquita et al. [28]	TM	HRmax > 220–age; RER > 1.1; VO_2 plateau	STEP Bruce protocol	1–2 min of slow walking +2 min at 0% incline at a speed eliciting 70%HRmax	Balke protocol TM grade was increased to 4% for 2 min and increased 2%/min	NR
Moreno-Cabañas et al. [14]	CE	VO_2 plateau; RER > 1.1; BLa 8 mM; HR < 5% from age-predicted HRmax	RAMP 3-min WU at 30 W for women, 50 W for men + 15–20 W/min	5 min active recovery at 30 W + 15 min seated recovery	2 min WU at 30 W for women, 50 W for men + cycling at 110% PPO	NR
Sawyer et al. [12]	CE	NR	RAMP 5 min WU 50 W + 30 W/min for men 25 W + 15 W/min for women	Active recovery for 5–10 min at 25 or 50 W	100% PPO	NR
Saynor et al. [29]	CE	NR	RAMP 3 min at 20 W + 10–25 W/min	5 min active recovery at 20 W + 10 min passive seated recovery	3 min at 20 W + cycling at 110% PPO	NR
Schaun et al. [21]	TM	$\Delta VO_2 \leq$ 150 mL/min; RER > 1.10; RPE ≥ 18; ± 10	STEP 3 min at 3 km/h + 0.5 km/h and 1% increments in speed and grade	10 min of passive recovery	2 min at 50% of peak speed/grade + 1 min at 70% peak speed/grade + exercise at 1	Difference in VO_2max between protocols < 3%

Study	Exercise Mode	Traditional VO_{2max} Criteria Adopted	VO_{2max} Protocol	Recovery Phase Protocol	VER Protocol [6][27]	VER vs. GXT Criteria [12][27][32]
		b/min of 220–age			stage higher than GXT	2
Schneider et al. [30]	CE	RER ≥ 1.1; HRmax ≥ 200 b/min–age BLamax ≥ 8 mM; RPE ≥ 18 2	2 20 W + 10 W/min STEP	10 min passive recovery	2 cycling at 110% PPO	VO_2max in VER does not exceed GXT-derived value by >3%
2 Werkman [24] et al. [31]	CE	VO_2 plateau; 2 HR > 95% age-predicted HRmax; RER > 1.0	[5][9][10][11][12][13][20][22][23][26][25][31][29] RAMP Unloaded cycling + 10 W/min < 120 cm; 15 W/min 120–150 cm; 20 W/min > 150 cm [30]	1 min [9][10][12][13][23][26][25] passive recovery + 1 min unloaded cycling 2	Test started with an increase in PO every 10 s based on each participant's height	2 NR
		VO_2 plateau;	STEP 4 min at 5.6			

Study	VO_{2max} GXT ($mL \cdot kg \cdot min^{-1}$)	GXT Duration (min)	VO_{2max} VER ($mL \cdot kg^{-1} \cdot min^{-1}$)	VER Duration (min)	HR_{max} GXT (b/min)	HR_{max} VER (b/min)	Results
Arad et al. [32]	28 ± 6	9.6 ± 1.6	30 ± 7 *	2.6 ± 0.5	170 ± 12	172 ± 9	VER elicited a higher VO_2peak versus GXT, although there was no difference in HRpeak.
Astorino et al. [9]	32 ± 4	10.5 ± 1.6	32 ± 5	2.7 ± 0.7	191 ± 9 *	187 ± 10	There was no difference in VO_2max between protocols, yet several participants demonstrated a higher VO_2max in response to VER. GXT revealed a higher HRmax versus VER.
Astorino et al. [20]	17 ± 4 SCI 24 ± 4 AB	7.4 ± 1.4	17 ± 4 SCI 26 ± 4 * AB	1.7 ± 0.3	161 ± 29 176 ± 17	160 ± 26 178 ± 12	Mean VO_2peak from VER was higher than GXT in the AB group, although VO_2peak was similar across protocols in SCI. There was no

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Study	VO_{2max} GXT (mL·kg·min^{-1})	GXT Duration (min)	VO_{2max} VER (mL·kg^{-1}·min^{-1})	VER Duration (min)	HR_{max} GXT (b/min)	HR_{max} VER (b/min)	Results
							difference in HRpeak across all groups between protocols.
Astorino et al. [13]	2.0 ± 0.4 L/min	NR	2.0 ± 0.3 L/min	1.5 ± 0.3	174 ± 13	174 ± 12	There was no difference in VO_2max or HRmax between protocols, although 5, 9, and 7 women revealed a verification VO_2max > 0.06 L/min higher versus GXT.
Bhammar et al. [24]	40 ± 4 NO 27 ± 4 OB	9.7 ± 2.4	43 ± 4 * NO 28 ± 3 OB	2.2 ± 0.5	189 ± 6 NO 190 ± 13 OB	184 ± 8 NO 188 ± 12 OB	All children exhibited higher mean VER VO_2max versus GXT, although there was no difference in HRmax.
Bhammar et al. [25]	31 ± 6	NR	32 ± 6	2.1 ± 0.3	180 ± 11	180 ± 7	There was no difference in VO_2max or HRmax between protocols, yet 3 of 11 participants exhibited a higher VO_2max during VER compared to GXT.
Bowen et al. [15]	14 ± 3	5.8–15.1 ± 0.5–1.9	15 ± 3	2.0 ± 0.4	117 ± 20	119 ± 26	Mean VO_2peak and HRpeak were not different between protocols and VO_2peak was confirmed in 60% of participants.
Causer et al. [26]	35 ± 8	9.3 ± 2.3	33 ± 7	1.5 ± 0.4	168 ± 15	NR	Mean VO_2peak did not differ between protocols, yet VER VO_2peak was higher than GXT in 21% of participants.
Dalleck et al. [10]	28 ± 6	10.1 ± 2.1	27 ± 6	2.5 ± 0.5	165 ± 11	164 ± 10	Mean VO_2max and HRmax were not different between protocols, although

Study	VO_{2max} GXT ($mL \cdot kg \cdot min^{-1}$)	GXT Duration (min)	VO_{2max} VER ($mL \cdot kg^{-1} \cdot min^{-1}$)	VER Duration (min)	HR_{max} GXT (b/min)	HR_{max} VER (b/min)	Results
							11% of subjects exhibited higher VO_2max and HRmax values with VER.
Frederike de Groot et al. [23]	34 ± 8	9.0 ± 4.0	35 ± 8	NR	184 ±20	NR	Mean VO_2peak was similar between protocols, yet 25% and 42% of participants showed a higher VO_2peak and HRpeak in VER versus GXT.
Leicht et al. [22]	23–40 ± 3–6	8.5–10.5 ± 0.5–2.5	NR	NR	125–188 ± 7–10	125–181 ± 7–15	VO_2peak and HRpeak did not differ between VER and GXT in all subgroups. Athletes tended to exhibit a lower VO_2peak in response to VER versus GXT.
Mahoney et al. [27]	3.4 ± 0.4 L/min	8.3 ± 0.4	3.4–3.6 ± 0.5 $L \cdot min^{-1}$	2.5–6.9 ± 0.4–2.5	175 ± 12	170–177 ± 13–17	VER performed at 90% PPO elicits greater VO_2max versus GXT, yet there was no difference in HRmax.
Misquita et al. [28]	19 ± 3	8.8 ± 1.9	20 ± 3 *	8.5 ± 1.9	156 ± 15	158 ± 14	VER revealed higher VO_2peak versus GXT, although HRpeak was similar.
Moreno-Cabañas et al. [14]	23 ± 8	7.9 ± 2.0	25 ± 8 *	2.1 ± 0.4	155 ± 15	156 ± 15	VER-derived VO_2peak was higher than GXT, although there was no difference in HRpeak. Forty percent of participants show underestimated VO_2peak in response to GXT that is confirmed with VER.

Study	VO_{2max} GXT (mL·kg·min^{-1})	GXT Duration (min)	VO_{2max} VER (mL·kg^{-1}·min^{-1})	VER Duration (min)	HR_{max} GXT (b/min)	HR_{max} VER (b/min)	Results
Sawyer et al. [12]	2 ± 1 L·min^{-1}	7.1 ± 1.9	2 ± 1 L·min^{-1}	1.9 ± 0.4	174 ± 16	177 ± 13 *	Mean VO_2max was not different between protocols, yet HRmax was higher in VER. Thirteen and 8 participants achieved a VO_2max and HRmax in response to VER that was ≥2% and 4–14 b/min higher than GXT.
Saynor et al. [29]	34 ± 3	8–12	NR	NR	187 ± 15	NR	VO_2max values are reproducible in this sample in response to GXT and VER.
Schaun et al. [21]	22 ± 5	12 ± 2	24 ± 6 *	4.7 ± 0.4	150 ± 16	152 ± 16	VO_2max was higher in response to VER versus GXT, although there was no difference in HRmax.
Schneider et al. [30]	21 ± 4	13.0 ± 2.9	21 ± 5 *	2.2 ± 0.3	150 ± 20	151 ± 21	VO_2max from VER was lower than GXT, although there was no difference in HRmax. Sixty-eight percent of participants showed a ‘true’ VO_2max with VER, although 32% elicited a 3–21% higher VO_2max.
Werkman et al. [31]	39 ± 7	11.0 ± 3.0	39 ± 9	4.0 ± 1.0	177 ± 12	179 ± 13	There was no difference in VO_2peak or HRpeak between protocols.
Wood et al. [11]	34 ± 7	8–12	34 ± 7	NR	180 ± 10	180 ± 10	Neither VO_2peak nor HRpeak were different between protocols.

2 … es exhibit … [12] … a higher … [9] … [13], with this … [27] … n studies … [9][12][13][14][15][30][20][27][32][26][25][24] … es having … [12][13][15][20][26] … 2 … here is no universal approach to confirm its attainment from graded exercise testing. Verification testing is another widely adopted method to perform this function, yet it has been criticized for requiring an additional intense effort that may be inappropriate in those who are not active or healthy. A prior review by Poole and Jones [33] emphasized the widespread implementation of verification testing to identify a ‘true’ VO_2max rather than ‘VO_2peak’ in healthy active adults. In contrast, recent work [19] in active young and older men concluded that verification testing is unnecessary

due to lack of differences in mean VO_2max between the incremental and verification-derived value. The current review adds to this dogma by summarizing existing results from a large population of unhealthy adults and children completing verification testing following a GXT. Obtaining the most accurate VO_2max value in this population is vital as it may lead to misrepresentations in their health status or responsiveness to training, which may in turn lead to inappropriate courses of treatment. Results reveal that most studies show no differences in aggregate VO_2max between protocols. However, six studies show that VER elicits significantly higher estimates of VO_2max, which supports its use when utmost accuracy is required in determining a 'true' VO_2max on that day of testing.

Identifying differences in VO_2max between GXT and VER requires that scientists are aware of the magnitude of error in VO_2max estimation for both protocols. The error inherent in repeated VO_2max testing ranges from 2–9% [7][14][26][34], with the error in acquiring gas exchange data from a metabolic cart being small (40 mL/min for the Parvo Medics system). This suggests that the remainder of the error is biological and likely related to participants' ability and motivation to tolerate near maximal exercise. We recommend that scientists perform repeated testing to develop typical error values for their lab and use these values when comparing individual VO_2max values between protocols rather than only comparing aggregate values. This approach, albeit time intensive, is preferred since relying on other laboratories' criterion values is inappropriate due to differences in exercise protocol, equipment, patient population, pre-test dietary and physical activity restrictions, and time averaging intervals, which likely induce small changes in oxygen uptake.

A primary criticism of supramaximal VER testing is that this effort is too intense for inactive, unhealthy, or deconditioned adults to tolerate, resulting in a very brief duration of exercise and greater potential to not attain VO_2max due to slow O_2 kinetics. However, data from multiple studies [12][15][26][25] using supramaximal VER with exercise duration <2 min exhibit no differences in VO_2max between protocols, similar to studies [9][10][25][31] in which VER duration lasted between 2–4 min. A recent study in hypertensive adults [21] used a multi-stage verification protocol eventually requiring a supramaximal workload. Results showed a significant underestimation of mean and individual VO_2max values in response to GXT compared to VER. In nine obese adults with VO_2max equal to 35 mL/kg/min [27], VER at 105% PPO elicited significantly lower exercise duration (167 s) compared to VER at 80% PPO (418 s), although there was no difference in VO_2max between tests. However, VER performed at 80 (+0.16 L/min, 5% higher) and 90% PPO led to a higher VO_2max value (+0.24 L/min, 7% higher) versus GXT, although this latter result was a trend (p = 0.06). Bhammar et al. [25] reported that a minimum exercise duration to attain a plateau in VO_2 in response to VER in patients with hypertension was 80 s. These results seem to indicate that the appropriate or minimum duration required to allow attainment of 'true' VO_2max using VER in unhealthy adults and children is similar to that recommended for healthy and active individuals. Thus, it is possible that submaximal intensities or multi-stage protocols may optimize VO_2max values compared to GXT, although additional work in larger samples is needed to confirm this result.

Our review corroborates results from healthy, fit adults [17][35] showing no difference in HRmax between GXT and VER. However, a subset of data presented in this study [35] from participants with average cardiorespiratory fitness, exhibited significantly lower HRmax (−3 b/min) in response to VER compared to GXT. This is likely a result of the stepwise protocol used in this study that is characterized by a work rate less than PPO eliciting VO_2max combined with a relatively long exercise duration (~20 min) versus the traditional 8–12 min ramp protocol. In contrast, obese adults performing VER at 100% PPO expressed significantly higher HRmax (+3 b/min) versus GXT [12], which may be attributed to their unfamiliarity with vigorous exercise during the initial incremental bout. To identify a ‘true’ VO_2max, Midgley and Carroll [36] denoted a difference in HRmax < 4 b/min between GXT and VER. This value encompasses the magnitude of differences in HRmax described in the above studies, so it is likely that these discrepancies in HRmax between protocols are not clinically meaningful.

Considerations as to the exact characteristics of the recovery interval between GXT and VER include the intensity of the verification test, duration of GXT, cardiorespiratory fitness of participants, as well as a potential need to reduce the overall time of the session. Our review (**Table 1**) shows durations as brief as 2–5 min between protocols [22][23][32][31][28], 5–15 min [13][14][15][21][22][26][24][29], to as long as several days between protocols [10][32]. A recent systematic review [17] concluded that there was no effect of recovery interval on the difference in VO_2max between protocols, which would suggest that any duration is appropriate. It is also apparent that some studies require an active recovery between protocols [13][15][20][28], whereas a passive recovery is completed in other investigations [11][14][21][23][25][24]. We recommend that scientists perform preliminary testing to identify an optimal recovery protocol for their specific population, and if this is implausible, then we recommend that they duplicate previously used procedures for that population.

Verification testing is only appropriate to identify ‘true’ VO_2max if it is safe and well-tolerated by the participant completing exercise testing. This factor is especially critical in persons unfamiliar with vigorous exercise who may face enhanced risk of complications during vigorous exercise. In male and female survivors of cancer, Schneider et al. [30] reported no adverse events in their participants performing VER at 110% PPO. Furthermore, use of VER in adults with heart failure [15], hypertension [25], and metabolic syndrome [14] was described as “feasible” and “well-tolerated” in these populations at risk for or having heart disease. In children with cystic fibrosis [29], it was labeled as “safe.” Although further work is needed to substantiate this, empirical results suggest that VER following GXT is a safe and well-tolerated procedure that does not induce contraindications to exercise testing in persons who are inactive, have known disease, or exhibit enhanced risk of cardiometabolic disease. This guideline encompasses all VER protocols requiring efforts at submaximal, maximal, or supramaximal work rates. The only disadvantage to VER seems to be the extra time commitment required of approximately 15–20 min, including the recovery between protocols. However, this extra time is acceptable if the primary goal of testing is to acquire the most precise estimate of VO_2max, which is critical in “at-risk” individuals when VO_2max testing is used to identify health status or determine the effects of exercise training.

There are a few limitations to this review. First, the marked diversity in patient populations used and the specific GXT and VER protocol completed preclude us from making universal recommendations regarding an optimal verification test. Nevertheless, it seems that submaximal or supramaximal work rates can be employed with little difference in resultant VO_2max values expected versus GXT. Second, with exception of a few studies [11][14][30][28], the sample size of individual studies is relatively small, which reduces the generalizability of these findings. Consequently, we recommend that scientists follow experimental procedures used in single studies that utilized their target population. Third, the use of VER following GXT likely elicits the highest estimate of VO_2max on that day, yet it is possible that additional testing on subsequent days could elicit higher estimates of VO_2max, as recently shown [37]. However, requiring multiple sessions of exercise including GXT and VER on many days may not be appropriate in unhealthy participants due to time and health related challenges.

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