REVIEW ARTICLE

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The Potential for High-Intensity Interval Training to Reduce Cardiometabolic Disease Risk

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Abstract

In the US, 34% of adults currently meet the criteria for the metabolic syndrome defined by elevated waist circumference, plasma triglycerides (TG), fasting glucose and/or blood pressure, and decreased high-density lipoprotein cholesterol (HDL-C). While these cardiometabolic risk factors can be treated with medication, lifestyle modification is strongly recommended as a first-line approach. The purpose of this review is to focus on the effect of physical activity interventions and, specifically, on the potential benefits of incorporating higher intensity exercise. Several recent studies have suggested that compared with continuous moderate exercise (CME), high-intensity interval training (HIT) may result in a superior or equal improvement in fitness and cardiovascular health. HIT is comprised of brief periods of high-intensity exercise interposed with recovery periods at a lower intensity. The premise of using HIT in both healthy and clinical populations is that the vigorous activity segments promote greater adaptations via increased cellular stress, yet their short length, and the ensuing recovery intervals, allow even untrained individuals to work harder than would otherwise be possible at steady-state intensity. In this review, we examine the impact of HIT on cardiometabolic risk factors, anthropometric measures of obesity and cardiovascular fitness in both healthy and clinical populations with cardiovascular and metabolic disease. The effects of HIT versus CME on health outcomes were compared in 14 of the 24 studies featuring HIT. Exercise programmes ranged from 2 weeks to 6 months. All 17 studies that measured aerobic fitness and all seven studies that measured insulin sensitivity showed significant improvement in response to HIT, although these changes did not always exceed responses to CME comparison groups. A minimum duration of 12 weeks was necessary to demonstrate improvement in fasting glucose in four of seven studies (57%). A minimum duration of 8 weeks of HIT was necessary to demonstrate improvement in HDL-C in three of ten studies (30%). No studies reported that HIT resulted in improvement of total cholesterol, low-density lipoprotein cholesterol (LDL-C), or TG. At least 12 weeks of HIT was required for reduction in blood pressure to emerge in five studies of participants not already being treated for hypertension. A minimum duration of 12 weeks was necessary to see consistent improvement in the six studies that examined anthropometric measures of obesity in overweight/obese individuals. In the 13 studies with a matched-exercise-volume CME group, improvement in aerobic fitness in response to HIT was equal to (5 studies), or greater than (8 studies) in response to CME. Additionally, HIT has been shown to be safe and effective in patients with a range of cardiac and metabolic dysfunction. In conclusion, HIT appears to promote superior improvements in aerobic fitness and similar improvements in some cardiometabolic risk factors in comparison to CME, when performed by healthy subjects or clinical patients for at least 8–12 weeks. Future studies need to address compliance and efficacy of HIT in the real world with a variety of populations.

1. Introduction

According to the 2003–6 National Health and Nutrition Examination Survey (NHANES), 34% of all adults in the US meet the criteria for the metabolic syndrome defined by the National Cholesterol Education Program's Adult Treatment Panel III (NCEP/ATP III).[1] The NCEP/ATP III criteria for the metabolic syndrome includes at least three of the following risk factors: increased waist circumference, elevated triglycerides (TG), low high-density lipoprotein cholesterol (HDL-C), elevated fasting glucose and elevated blood pressure.[2]

While these cardiometabolic risk factors can be treated effectively with medication, lifestyle modification is strongly recommended as a first-line approach.[3] Most lifestyle intervention programmes include behavioural, dietary and physical activity components, but there is evidence that regular exercise decreases cardiometabolic risk independent of dietary intervention.[4,5] Furthermore, regular aerobic exercise also improves cardiovascular fitness,[6,7] a health and function benefit that is not expected with a medication-only treatment plan. Multiple studies have shown an association between cardiovascular fitness and cardiovascular mortality, as well as all-cause mortality in men and women of all ages.[8-10] Thus, there is strong rationale to emphasize exercise within lifestyle improvement programmes that are designed to prevent or treat the metabolic syndrome and its components.

Despite evidence that exercise is vital to good health and disease prevention, only 64.5% of adults in the US meet federal recommendations of at least 150 minutes/week of moderate-intensity or 75 minutes/week of vigorous-intensity aerobic exercise.[11] One commonly cited barrier to exercise is a lack of time.[12] Substituting some vigorous exercise for some moderate-intensity exercise is a way to improve fitness in a more time-efficient manner. According to the 2008 Physical Activity Guidelines,[5] 1 minute of vigorous activity counts for 2 minutes of moderate-intensity activity, although currently there is not sufficient evidence to support this claim for many health outcomes. Nevertheless, including vigorous activity as part of an exercise programme could offer a more time-efficient approach to achieve specific health goals for some individuals. In this review, we examine the impact of high-intensity interval training (HIT) on aerobic fitness and metabolic outcomes.

HIT may offer similar health benefits compared with continuous moderate aerobic exercise (CME),[13] and may be more time-efficient for improving maximal oxygen consumption ($\dot{V}O_{2max}$).[14,15] HIT has been used for several decades by athletes and coaches to improve exercise performance,[16] but its ability to improve health outcomes in non-athletes has recently generated new interest. HIT is characterized by brief periods of high-intensity aerobic exercise (typically >90% $\dot{V}O_{2max}$) separated by recovery periods of lower-intensity aerobic exercise or rest.[17] The recovery periods allow for brief periods of high-intensity exercise that would not be sustainable for longer periods of continuous exercise. As a result of exercising at high intensity, a shorter total duration of each exercise session is required to complete an equal volume of work compared with CME. Therefore, HIT may provide an alternative mode of vigorous exercise for people who do not possess the necessary fitness level to perform continuous high-intensity exercise.

The purpose of this review is to examine the impact of HIT on clinical cardiometabolic risk factors including glucose metabolism, serum lipids, blood pressure and anthropometric outcomes, including body mass index (BMI), body composition and waist circumference. Additionally, $\dot{V}O_{2max}$, while not a typical measurement of cardiometabolic risk in most clinical settings, is highly predictive of all-cause and cardiovascular mortality.[9,10] The literature on aerobic exercise training responses is mostly comprised of studies that used CME. Thus, to determine the equivalency or relative benefits of HIT, many HIT studies have included a CME arm in which the training volume (exercise energy expenditure) was similar to or greater than the HIT arm.

A literature search of the PubMed database was performed in March 2011 using the following terms: 'high-intensity interval training' or 'high-intensity interval exercise' combined with 'weight loss', 'obesity', 'body fat', 'diabetes', 'glucose', 'insulin', 'metabolic syndrome' and 'lipids'. Additional relevant publications were identified by using the PubMed 'related articles' link, as well as reviewing the reference sections from the selected studies. A similar search strategy was employed using the OVID MEDLINE and SPORTDiscus™ databases. Search results were limited to studies examining HIT and at least one clinical cardiometabolic risk factor, studies examining non-athletes/untrained participants, longitudinal studies and English language articles. Cross-sectional studies, animal studies, studies including diet interventions with HIT, studies examining outcomes in trained participants/athletes and studies examining only non-clinical outcomes were excluded. Twenty-four peer-reviewed original research articles were included in this review. Fourteen of those studies were conducted as randomized trials with a CME arm and 14 included a control non-exercise arm. Only one of the included studies was conducted in adolescents,[18] and there were no studies in prepubescent children. No year limit was applied, and the earliest study found was from 1984. Studies included participants who had normal BMI (18.5–24.9 kg/m^2), as well as studies with overweight/obese participants (≥25.0 kg/m^2). While most of the studies included healthy participants, five studies included participants with cardiovascular disease,[19-23] one study included participants with the metabolic syndrome,[24] and one study included participants with type 2 diabetes mellitus.[25] While studies utilizing specific dietary interventions in combination with HIT were excluded, one study included a 1-hour diet education seminar prior to the start of training that had no apparent effect on energy intake.[26] Study durations ranged from 2 weeks to 6 months.

2. High-Intensity Interval Training: Operational Definition

HIT is defined as vigorous exercise performed at a high intensity for a brief period of time interposed with recovery intervals at low-to-moderate intensity or complete rest. The modes of HIT training usually include running/walking on a treadmill or cycling on a cycle ergometer. HIT does not include resistance training. Two distinct types of HIT are included in this review. Sprint interval training (SIT) is usually characterized by 4–6 cycles of 30 second 'all out sprints' followed by 4–4.5 minutes of recovery. Five SIT studies are included in this review. Four SIT studies used leg cycle ergometry as the mode of exercise,[14,27-29] and one study used treadmill running.[30] The extremely high intensity of SIT imposes some potential health, safety and motivational concerns. Therefore, the majority of studies using this approach have been performed with young healthy people, although a few recent studies have begun exploring whether SIT could be used in clinical populations.[29,31] The other type of HIT, aerobic interval training (AIT), is performed at a slightly lower intensity than SIT but for longer periods of time. Typically, the AIT exercise protocols in this review used 4 minutes of high-intensity work at 80–95% $\dot{V}O_{2max}$ followed by 3–4 minutes of recovery time, for 4–6 cycles performed on a treadmill or bicycle ergometer. In contrast to SIT, the AIT approach has been used with young healthy people and higher risk groups, including older adults and patients with coronary artery disease (CAD).[20-23] Many of the studies in this review include a CME arm for comparison with HIT. In contrast to SIT and AIT, CME is typically performed at 50–75% $\dot{V}O_{2max}$. Some of these studies that compared results of HIT versus CME controlled for the total energy expenditure during exercise. Thus, in order to achieve equal energy expenditure, participants in the CME training arms typically exercised ~15–20% longer than their AIT counterparts. However, energy expended during exercise has not always been matched among comparison training groups. This is especially true for the studies using SIT, in which the total exercise time may be only 2–3 minutes and the comparison CME group may perform a traditional moderate-intensity exercise session for 45–60 minutes.[14]

2.1 Maximal Oxygen Consumption Outcomes

The 17 studies that examined the impact of HIT on $\dot{V}O_{2max}$ consisted of three SIT studies of 2- to 6-weeks' duration[14,29,30] and 14 AIT studies of 4-weeks' to 6-months' duration (table I). All but one treatment arm of a single study[35] demonstrated an increase in $\dot{V}O_{2max}$ after the SIT/AIT programmes. All four studies of 4- to 8-weeks' duration that included a CME arm, induced a similar improvement in $\dot{V}O_{2max}$ in both the SIT/AIT and CME arms. Two of those investigations used the SIT approach with young adults[14,30] and the other two studies used AIT in older adults with CAD[19] and overweight/obese middle-aged adults.[26]

Nine AIT studies that lasted 10 weeks to 6 months also included a CME arm. In contrast to the studies comparing SIT with CME, all but one of the AIT studies reported that AIT resulted in a significantly greater improvement in $\dot{V}O_{2max}$ compared with CME training.[35] This includes three studies in adults with CAD,[20-22] three studies in young adults,[15,38,39] a study in obese, middle-aged adults[37] and a study in middle-aged adults with the metabolic syndrome.[24] An exception to those findings was presented by Thomas et al.[35] In that study, statistically similar improvement in $\dot{V}O_{2max}$ was achieved by the CME group and an AIT group who performed 4×4-minute bouts of vigorous activity, although a second AIT group who performed 8×2-minute bouts of high-intensity exercise had no improvement in $\dot{V}O_{2max}$ over the 11-week training programme. It is possible that the relatively small group sizes (nine adults in the 8×2-minute bout group) may have obscured the ability to detect significantly different training responses in that study.

Notably, AIT induced equal or superior improvement in $\dot{V}O_{2max}$ in comparison with CME, even when exercise time was less in the AIT group. Due to the higher intensity of exercise, AIT exercise sessions required less time than CME sessions to

Table I. Summary of cardiometabolic outcomes from studies using high-intensity interval training

Study	Participant characteristics[a,b]	Study design	Sample size (n)	Intensity/duration of exercise	Glucose regulation[c,d]	Lipids[d,e]	BP[d,f]	Anthropometric measurements[d]	$\dot{V}O_{2max}$[d]
Babraj et al.[28]	16 young men, normal BMI	Cycle ergometer, 6 sessions in 2 wk	SIT (16)	4–6×30 sec 'all-out' sprints, 4 min recovery 17–26 min/session 250 kcal/wk	OGTT AUC: glucose ↓12% insulin ↓37% insulin sensitivity (Cederholm index) ↑23% No change in fasting glucose or insulin				
Richards et al.[27]	31 young adults, overweight	Cycle ergometer, 6 sessions in 2 wk	SIT (12) SB (9) CON (10)	SIT: 4–7×30 sec 'all-out' sprints, 4 min recovery SB: as above for only 1 training session	Insulin sensitivity (clamp technique): SIT ↑27% No change in single bout or CON No change in fasting glucose or insulin				
Whyte et al.[29]	10 young men, overweight/obese	Cycle ergometer, 6 sessions in 2 wk	AIT (10)	4–6×30 sec 'all-out' sprints, 4.5 min recovery	24 h post-exercise, fasting insulin ↓25%, insulin AUC ↓15% Insulin sensitivity Index ↑23% Changes did not persist 72 h post-exercise No change in fasting glucose or glucose AUC	No change in TC, TG or HDL-C	SBP ↓5% at 24 h, change did not persist at 72 h No change in DBP	No change in body mass WC ↓1.1%	↑9.5%
Little et al.[25]	8 older adults with type 2 diabetes mellitus, obese	Cycle ergometer, 6 sessions in 2 wk	AIT (8)	10×60 sec at 90% HR_{max} with 60 sec recovery plus warm up/cool down Total time: 75 min/wk	48 h results: Continuous 24 h average blood glucose ↓13.2% AUC 24 h glucose ↓13.5% 3 h post-prandial glucose AUC ↓29.6%				

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Table I. Contd

Study	Participant characteristics[a,b]	Study design	Sample size (n)	Intensity/duration of exercise	Glucose regulation[c,d]	Lipids[d,e]	BP[d,f]	Anthropometric measurements[d]	$\dot{V}O_{2max}$[d]
Hood et al.[32]	7 middle-aged adults, overweight	Cycle ergometer, 6 sessions in 2 wk	AIT (7)	10×60 sec at 80–95% HR_{res} with 60 sec recovery plus warm up/cool down ~20 min/session	72 h results: Insulin sensitivity (HOMA2%S) ↑35%				
Moholdt et al.[19]	59 older adults, overweight, post coronary artery bypass graft surgery	Treadmill, 5×/wk for 4 wk	AIT (28) CME (31)	AIT: 4×4 min at 90%HR_{max} with 3 min recovery plus warm up/cool down Total time: 38 min/session CME: continuous exercise at 70% HR_{max} for 46 min/session, similar energy expenditure as AIT	No change in fasting glucose (fasting glucose elevated at baseline)	No change in HDL-C, LDL-C, or TG		No change in body weight	AIT ↑12.2% CME ↑8.8% No difference between groups
Burgomaster et al.[14]	20 young adults, normal BMI	Cycle ergometer, SIT: 3×/wk for 6 wk CME: 5×/wk for 6 wk	SIT (10) CME (10)	SIT: 4–6×30 sec 'all-out' sprints, 4.5 min recovery 1.5 h/wk CME: 40–60 min continuous exercise at 65% $\dot{V}O_{2peak}$ 4.5 h/wk				No change in body weight	SIT ↑7.3% CME ↑9.8% No difference between groups
Macpherson et al.[30]	20 young adults, baseline BMI NR, but calculated from data provided as normal/borderline overweight	Treadmill, 3×/wk for 6 wk	SIT (10) CME (10)	SIT: 4–6×30 sec 'all-out' sprints, 4 min recovery CME: 65% $\dot{V}O_{2max}$, 30–60 min/session				Fat mass (kg): SIT ↓12.4% CME ↓5.8% Lean mass (kg): ↑1.0% in both groups	SIT ↑11.5% CME ↑12.5% No difference between groups
Musa et al.[33]	36 young men, normal BMI	Running, 3.2 km on track 3×/wk for 8 wk	AIT (20) CON (16)	AIT: 4×800 m runs at 90% HR_{max} with 1 : 1 exercise-to-rest time ratio ~40 min/session		HDL-C: AIT ↑18.1% TC/HDL-C ratio: AIT ↓18.1% No change in TC		No change in BMI or BF%	

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Table I. Contd

Study	Participant characteristics[a,b]	Study design	Sample size (n)	Intensity/duration of exercise	Glucose regulation[c,d]	Lipids[d,e]	BP[d,f]	Anthropometric measurements[d]	$\dot{V}O_{2max}$ [d]
Tsekouras et al.[34]	15 young men mean BMI: 25.2 kg/m^2 (borderline overweight)	Treadmill, 3×/wk for 8 wk	AIT (7) CON (8)	AIT: 4×4 min at 90% $\dot{V}O_{2peak}$, 4 min recovery, 32 min/session		VLDL-C-TG: AIT ↓28%		No change in body weight or composition	AIT ↑18%
Wallman et al.[26]	21 middle-aged, obese adults	Cycle ergometer, 4×/wk for 8 wk plus a 1 h diet education seminar prior to start of training	AIT (7) CME (6) CON (8)	AIT: 10×1 min at 90% $\dot{V}O_{2peak}$, 2 min recovery at 30% $\dot{V}O_{2peak}$, 30 min/session CME: 30 min continuous exercise at 50% $\dot{V}O_{2peak}$, similar energy expenditure as AIT		No change in TC, HDL-C, LDL-C or TG (TC elevated at baseline)	No change in BP	No change in body mass Upper body fat mass: AIT ↓8% CME ↓3% No change in energy intake for all 3 groups	AIT ↑24% CME ↑19% No difference between groups
Rognmo et al.[20]	17 adults with CAD, overweight	Treadmill, 3×/wk for 10 wk	AIT (8) CME (9)	AIT: 4×4 min at 80–90% $\dot{V}O_{2peak}$, 3 min recovery, plus warm up/cool down, 33 min/session CME: 41 minutes continuous exercise at 50–60% $\dot{V}O_{2peak}$, similar energy expenditure as AIT			No change in resting BP (SBP elevated at baseline)	No change in body mass	AIT ↑17.9% CME ↑7.9% AIT ↑ more than CME ($p < 0.01$)
Thomas et al.[35]	36 young men 18–25 y (BMI NR)	Treadmill, 3×/wk for 11 wk	AIT-1 (8) AIT-2 (9) CME (11) CON (8)	AIT-1 : 6×4 min at 90–100% HR_{max}, 4 min recovery AIT-2 : 8×2 min at 90–100% HR_{max}, 3 min recovery CME: 8.04 km at 75–85% HR_{max} (8 min/mile), time not given Similar energy expenditure among groups		No change in TC or HDL-C			AIT-1 ↑19.9% AIT-2: no change CME: ↑7.1%

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Table I. Contd

Study	Participant characteristics[a,b]	Study design	Sample size (n)	Intensity/duration of exercise	Glucose regulation[c,d]	Lipids[d,e]	BP[d,f]	Anthropometric measurements[d]	$\dot{V}O_{2max}$[d]
Moreira et al.[36]	23 middle-aged adults, overweight	Cycle ergometer, 3 ×/wk for 12 wk	AIT (8) CME (8) CON (7)	AIT: 20×2 min at 20% above anaerobic threshold, 1 min no-exercise recovery, 60 min/session CME: 60 min continuous exercise at 10% below anaerobic threshold, similar energy expenditure as AIT	Fasting glucose[g]: AIT ↓13% CME ↓14%	TC[g]: AIT no change CME ↓ 16% TG: no change		BMI: AIT ↓1.4% CME ↓1.5% WC: HIT ↓0.8% CME ↓1.8% WHR: HIT ↓2.5% CME no change BF%: HIT ↓0.6% CME ↓0.9% All outcomes not different between groups	
Nybo et al.[15]	28 young men BMI NR, Mean body fat: 24.3%	Treadmill, 3 ×/wk for 12 wk AIT group: completed 2.0±0.1 mean±SD sessions/wk CME group: completed 2.5±0.2 mean±SD sessions/wk	AIT (8) CME (9) CON (11)	AIT: 5×2 min intervals at 95% HR_{max}, recovery duration NR, plus 5 min warm up. 20 min/session CME: continuous running at 80% HR_{max} for 60 min	Fasting glucose: AIT ↓9% CME ↓9% Glucose (2 h post-glucose load): AIT ↓16.4% CME ↓12.5% (fasting glucose elevated at baseline)	No change in TC, HDL-C, LDL-C TC/HDL-C ratio: AIT no change CME ↓15%	SBP: AIT ↓6% CME ↓6% DBP: AIT no change CME ↓6%	Body mass: AIT no change CME ↓1.2% BF%: AIT no change CME ↓1.7%	AIT ↑14.2% CME ↑7% AIT ↑ more than CME ($p<0.05$)
Schjerve et al.[37]	27 middle-aged adults, obese	Treadmill, 3 ×/wk for 12 wk 2 supervised sessions and 1 at-home session/wk	AIT (14) CME (13)	AIT: 4×4 min intervals at 85–95% HR_{max} with 3 min recovery, plus warm up/cool down, 38 min/session CME: continuous exercise at 60–70% HR_{max} for 47 min, similar energy expenditure as AIT	No change in fasting glucose, insulin, C-peptide, or HbA_{1c}	No change in TC, HDL-C, or TG (TC elevated at baseline)	No change in SBP DBP: AIT ↓7% CME ↓9% (DBP elevated at baseline)	Body weight: AIT ↓2% CME ↓3% BMI: AIT ↓1.6% CME ↓3.0% BF%: AIT ↓2.2% CME ↓2.5% No change in WHR	AIT ↑33% CME ↑16% AIT ↑ more than CME ($p<0.001$)

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Table I. Contd

Study	Participant characteristics[a,b]	Study design	Sample size (n)	Intensity/duration of exercise	Glucose regulation[c,d]	Lipids[d,e]	BP[d,f]	Anthropometric measurements[d]	$\dot{V}O_{2max}$[d]
Thomas et al.[38]	59 young adults 18–32 y (BMI NR) Mean BF% males, 14.5%; females, 24.5%	Treadmill, 3×/wk for 12 wk	AIT (15) CME-1 (14) CME-2 (18) CON (12)	AIT: 8×1 min at 90% HR_{max}, 3 min recovery, 500 kcal/session CME-1: 4 miles at 75% HR_{max}, 500 kcal/session CME-2: 2 miles at 75% HR_{max}, 250 kcal/session		No change in TC, TG, or HDL-C		BF%[g]: All exercise groups ↓BF%~3%	AIT ↑10.2% No change in other groups
Tjonna et al.[18]	42 adolescents, mean age 14 y, obese	Treadmill, 2×/wk for 12 wk	AIT (20) CON (22)	AIT: 4×4 min intervals at 95% HR_{max} with 4 min recovery plus warm up/cool down, 40 min/session CON: group meetings every 2 wk, undefined group physical activity sessions 3 times in 3 mo	Fasting glucose: AIT ↓6% CON no change Fasting insulin: AIT ↓29% CON ↓19% Glucose (2 h post glucose load): AIT ↓12% CON no change Insulin (2 h post-glucose load): AIT ↓27% CON ↓41% Insulin sensitivity (HOMA2%S): AIT ↑24% CON ↑10% HbA_{1c}: AIT ↓0.14% CON ↓0.13%	HDL-C: AIT ↑9.7% CON no change No change in TG	SBP: AIT ↓7% CON ↓2% DBP: AIT ↓8% CON no change MAP: AIT ↓8% CON no change	BMI: AIT ↓2.1% CON no change BF% AIT↓1.3% CON no change No change in WC	AIT↑11% CON no change

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Table I. Contd

Study	Participant characteristics[a,b]	Study design	Sample size (n)	Intensity/duration of exercise	Glucose regulation[c,d]	Lipids[d,e]	BP[d,f]	Anthropometric measurements[d]	$\dot{V}O_{2max}$[d]
Wisloff et al.[21]	27 older adults with post-infarction heart failure, normal BMI	Treadmill, supervised training 2×/wk plus at-home outdoor walking 1×/wk for 12 wk	AIT (9) CME (9) CON (9)	AIT: 4×4 min at 90–95% HR_{peak}, 3 min recovery, plus warm up/cool down, 38 min/session CME: continuous walking at 70–75% HR_{peak} for 47 min, similar energy expenditure as AIT CON: advised to follow advice from physician regarding exercise plus supervised treadmill walking once every 3 wk at 70% HR_{peak} for 47 min	No change in fasting glucose (fasting glucose elevated at baseline)	No change in TC, TG or HDL-C (TC elevated at baseline)	No change in BP (participants were on BP medications)	No change in BMI	AIT ↑46% CME ↑14% AIT ↑ more than CME ($p<0.05$) CON no change
Ciolac et al.[39]	34 healthy, normotensive young women with family history of hypertension, normal BMI	Treadmill, 3×/wk for 16 wk	AIT (11) CME (11) CON (12)	AIT: 13×1 min at 80–90% $\dot{V}O_{2max}$, 2 min recovery, 40 min/session CME: continuous exercise at 60–70% $\dot{V}O_{2max}$ for 40 min, similar energy expenditure as AIT	Fasting glucose: No change Insulin: AIT ↓35% CME ↓28% Insulin sensitivity (HOMA2%S): AIT ↑31% CME ↑27%	TC, HDL-C, LDL-C and TG did not change	Ambulatory SBP: AIT ↓1.8% CME ↓2.4% Ambulatory DBP: AIT ↓2.8% CME ↓3.0%	BMI, WC, and WHR did not change	AIT ↑15.8% CME ↑8.0% AIT ↑ more than CME ($p<0.05$)
Guimaraes et al.[40]	43 middle-aged adults with hypertension, overweight	Treadmill, 3×/wk(2 supervised and 1 unsupervised session) for 16 wk	AIT (16) CME (16) CON (11)	AIT: 13×1 min at 80% HR_{res}, 2 min recovery at 50%HR_{res}, 40 min/session CME: continuous exercise at 60%HR_{res}, 40 min/session			BP did not change in any of the groups when analysed separately[h] (participants were on BP medications)		

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Table I. Contd

Study	Participant characteristics[a,b]	Study design	Sample size (n)	Intensity/duration of exercise	Glucose regulation[c,d]	Lipids[d,e]	BP[d,f]	Anthropometric measurements[d]	$\dot{V}O_{2max}$[d]
Tjonna et al.[24]	28 middle-aged adults with the metabolic syndrome, overweight	Treadmill, 3 ×/wk for 16 wk	AIT (11) CME (8) CON (9)	AIT: 4 × 4 min intervals at 95% HR_{max}, 3 min recovery, plus warm up/cool down, 40 min/session CME: continuous exercise at 70% HR_{max} for 47 min, similar energy expenditure as AIT CON: followed advice from family physician	Fasting glucose: AIT ↓4.3% CME no change Insulin sensitivity (HOMA2%S): AIT ↑15% CME no change (fasting glucose elevated at baseline)	HDL-C: AIT ↑22% CME no change (HDL-C low at baseline) TG: no change	SBP: AIT ↓6.2% CME ↓7.6% DBP: AIT ↓6.3% CME no change MAP: AIT ↓5.4% CME ↓6.9% (BP elevated at baseline)	Body weight: AIT ↓3% CME ↓4% BMI: AIT ↓2.3% CME ↓4.1% WC: AIT ↓4.7% CME ↓5.7% WHR: no change	AIT ↑35% CME ↑16% AIT ↑ more than CME ($p < 0.05$)
Warburton et al.[22]	14 middle-aged men with CAD, treated with bypass or angioplasty, overweight	Treadmill, stair climber, and cycle ergometer, 2 ×/wk for 16 wk plus continuous exercise at 65% $HR_{res}/\dot{V}O_{2res}$ 3 ×/wk for both groups	AIT (7) CME (7)	AIT: 8 × 2 min at 90% $HR_{res}/\dot{V}O_{2res}$, 2 min recovery, 30 min/session (10 min/equipment) CME: continuous exercise at 65% $HR_{res}/\dot{V}O_{2res}$, 30 min/session (10 min/equipment)			No change in SBP or DBP (participants were on BP medications)	Body mass: AIT ↓3.4% CME ↓4.7%	$\dot{V}O_2$ at anaerobic threshold: AIT ↑31.8% CME ↑9.5% AIT ↑ more than CME ($p < 0.05$)
Munk et al.[23]	40 middle-aged adults with coronary artery stents, overweight	Cycle ergometer or running, 3 ×/wk for 6 mo	AIT (20) CON (20)	4 × 4 min at 80–90% HR_{max}, 3 min recovery, plus warm up/cool down 33 min/session			No change in BP +BP medications	BMI: AIT ↓2.2% CON ↑1.8%	AIT ↑16.8% CON ↑7.8% AIT ↑ more than CON ($p < 0.01$)

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a Mean ages of participants: young (18–39 y), middle-aged (40–59 y), older (over 60 y).

b Mean BMI values of participants: normal BMI (18.5–24.9 kg/m^2), overweight (25.0–29.9 kg/m^2), obese (≥30 kg/m^2).

c Elevated baseline fasting glucose defined as ≥100 mg/dL or ≥5.6 mmol/L, baseline values were normal unless otherwise noted.

d Percentage change values given for post-exercise differences from baseline reaching statistical significance ($p < 0.05$), unless otherwise noted.

e Elevated baseline TC defined as ≥200 mg/dL or ≥5.2 mmol/L, elevated LDL-C: ≥160 mg/dL or ≥4.1 mmol/L, elevated TG: ≥200 mg/dL or ≥2.3 mmol/L, low HDL-C: <40 mg/dL or <1 mmol/L for men and <50 mg/dL or <1.3 mmol/L for women, baseline values were normal unless otherwise noted.

f Hypertension defined as SBP ≥140 or DBP ≥90, baseline values were normal unless otherwise noted.

g Authors did not provide absolute numbers. Percentage change is approximate, estimated from bar graphs.

h Authors reported that mean 24 h and daytime DBP decreased after training when both exercise groups were analysed together. The decrease in DBP was greater in subjects with baseline BP above the median value, but there was no difference between training programmes.

AIT = aerobic interval training; **AIT-1 and -2** = AIT groups 1 and 2; **AUC** = area under the curve for a variable measured serially; **BF%** = body-fat percentage; **BMI** = body mass index; **BP** = blood pressure outcomes; **CAD** = coronary artery disease; **CME** = continuous moderate-intensity exercise; **CME-1 and -2** = CME groups 1 and 2; **CON** = control group performing no intervention unless otherwise stated; **DBP** = diastolic blood pressure; **HbA_{1c}** = glycosylated haemoglobin; **HDL-C** = high-density lipoprotein cholesterol; **HOMA2%S** = homeostatic model assessment version 2 for insulin sensitivity; **HR_{max}** = maximal heart rate; **HR_{peak}** = peak HR; **HR_{res}** = HR reserve; **LDL-C** = low-density lipoprotein cholesterol; **MAP** = mean arterial pressure; **NR** = not reported; **OGTT** = oral glucose tolerance test; **SB** = single bout; **SBP** = systolic blood pressure; **SD** = standard deviation; **SIT** = sprint interval training; **TC** = total cholesterol; **TG** = triglyceride concentration; **VLDL** = very low-density lipoprotein particle; **$\dot{V}O_{2max}$** = maximal oxygen uptake as a measure of aerobic exercise capacity; **$\dot{V}O_{2peak}$** = peak $\dot{V}O_2$; **WC** = waist circumference; **WHR** = waist-to-hip ratio; ↓ indicates decreased; ↑ indicates increased.

achieve the same energy expenditure. Four AIT studies of 10- to 12-weeks' duration in which exercise energy expenditure was matched in the AIT and CME groups showed a significantly greater increase in $\dot{V}O_{2max}$ in the AIT groups.[20,21,24,37] Additionally, one AIT study of only 4-weeks' duration resulted in an equal improvement in $\dot{V}O_{2max}$ in both the AIT and CME groups.[19] All five of these studies required 15–20% less time in the AIT group to achieve the same energy expenditure as the CME group. Furthermore, in the 12-week AIT study by Nybo et al.,[15] the AIT group, which exercised for only 20 minutes/session, demonstrated a significantly greater increase in $\dot{V}O_{2max}$ compared with the CME group, which exercised for 1 hour. Exercise energy expenditure for each group was not reported, however.

Similarly, SIT studies that included a CME arm demonstrated comparable increases in $\dot{V}O_{2max}$ even when exercise time and/or training volume/energy expenditure were much less in the SIT arm. In the 6-week study by Burgomaster et al.,[14] young adults had similar increases in $\dot{V}O_{2max}$ in both the SIT and CME groups. SIT training volume in this study was only 10% of CME training volume, and total time was 1.5 hours/week for the SIT group compared with 4.5 hours/week for the CME group. Likewise, in the 6-week study by Macpherson et al.,[30] both the SIT and CME groups demonstrated similar improvement in $\dot{V}O_{2max}$. In this study, total exercise time was 6.75 hours/week in the SIT group and 13.5 hours/week in the CME group (energy expenditure was not reported).

Collectively, the available research strongly suggests that both SIT and AIT induce significant increases in $\dot{V}O_{2max}$ even when compared with CME training of longer time duration and similar or greater exercise energy expenditure. Furthermore, in a SIT study of only 2-weeks' duration and an AIT study of only 4-weeks' duration, both resulted in a significant improvement in $\dot{V}O_{2max}$ suggesting that HIT rapidly induces changes in $\dot{V}O_{2max}$ within a few training sessions.[19,29] In conclusion, HIT consistently induced significant changes in $\dot{V}O_{2max}$ in a wide variety of populations including adolescents,[18] young adults,[15] middle-aged adults[24] and older adults with CAD.[23] An increase in $\dot{V}O_{2max}$ appears to be the most common outcome from HIT.

2.2 Glucose Metabolism Outcomes

Thirteen studies examined the impact of HIT on measures of glucose metabolism, such as insulin sensitivity, fasting glucose concentration and results from oral glucose tolerance testing (table I). The methods used to measure insulin sensitivity in seven of these studies included the hyperinsulinaemic euglycaemic clamp technique,[27] Cederholm index,[28] homeostasis model assessment of fasting glucose and insulin [18,24,32,39] and the Matsuda insulin sensitivity index from an oral glucose tolerance test.[29] All seven of these studies showed significant improvement in insulin sensitivity after HIT.[18,24,27-29,32,39] In three of these studies, young adults performed SIT for 2 weeks on a cycle ergometer.[27-29] Of these three studies, Whyte et al.[29] found that insulin sensitivity was improved for 24 but not 72 hours after the last exercise session. In contrast, the other two SIT studies reported that insulin sensitivity increased above the pre-training values at a single measurement performed 48–72 hours after the last training session.[27,28] A single AIT study of only 2-weeks' duration showed significant improvement in insulin sensitivity in overweight middle-aged adults who performed only 20 minutes of exercise on a cycle ergometer.[32] Three other treadmill AIT studies of 12- to 16-weeks' duration demonstrated improvement in insulin sensitivity in overweight/obese adolescents;[18] healthy, young women with a family history of hypertension;[39] and middle-aged adults with the metabolic syndrome.[24] Of the two AIT studies that included a CME arm, one study showed similar improvement in both groups,[39] and the other study, performed with middle-aged adults with the metabolic syndrome, showed improvement only in the AIT group.[24] These results suggest that AIT can be an effective strategy to improve insulin sensitivity in patients who have already developed the metabolic syndrome.

Eleven studies evaluated the effect of HIT on fasting glucose concentration. The three SIT studies of 2- to 4-weeks' duration reported no change in participants with normal fasting glucose values at baseline,[27-29] and older adults with CAD and elevated fasting glucose.[19] In the seven AIT studies of 12–16 weeks, fasting glucose responses were inconsistent. Four of these studies reported a reduction in fasting glucose in participants with normal,[18,36] elevated[24] and borderline[15] fasting glucose values before training. In contrast, three AIT studies showed no change in fasting glucose values in participants with normal[37,39] or elevated[21] fasting glucose at baseline. Six of these studies included a CME arm. Three of these studies showed no change in fasting glucose in either the AIT or the CME arm,[21,37,39] two studies showed similar reduction in both the AIT and CME arms[15,36] and one study showed reduction in the AIT group only.[24]

All five HIT studies that reported values for the oral glucose tolerance test (OGTT) reported significant improvement in 2-hour glucose or glucose area under the curve (AUC) measurements.[15,18,25,28,29] Two of these were SIT studies of 2-weeks' duration in young men.[28,29] Whyte et al.[29] reported a decrease in the insulin AUC at 24 hours, but this improvement did not persist at 72 hours post-exercise. One AIT study of only 2-weeks' duration reported a decrease in glucose AUC in older adults with type 2 diabetes mellitus who performed 75 minutes/week of exercise on a cycle ergometer.[25] The other two were AIT studies of 12-weeks' duration with overweight/obese adolescents[18] and young, healthy men.[15] The study by Nybo et al.[15] included a CME arm, and both groups demonstrated similar improvement in 2-hour glucose values despite the 20-minute training time in the AIT group compared with 1 hour in the CME group.

In summary, the research suggests that HIT results in a significant improvement in insulin sensitivity in a variety of populations and may be equal or superior to the effect of CME. SIT studies and/or studies of less than 12-weeks' duration did not show a change in fasting glucose. Results of studies of at least 12-weeks' duration were inconsistent, but the outcomes suggest that AIT may be more effective in lowering fasting glucose in young or middle-aged adults than in older adults. A notable exception was the improvement in oral glucose tolerance, which was recently demonstrated in older people with type 2 diabetes.[25] When compared with CME, AIT seems to be at least as effective in lowering fasting glucose in those cases where a reduction was reported. Studies of both SIT and AIT all showed improvement in at least one value from the OGTT, and the one study that included a CME arm showed similar improvement in the OGTT, even with training time of 20 minutes in the AIT group compared with 1 hour in the CME group.[15] Whyte et al.[29] reported significant changes in insulin sensitivity and insulin AUC at 24 hours that did not persist at 72-hours post-exercise. Other authors showed significant results at 48 and 72 hours, but many did not report the timeline for testing glucose metabolism from the last bout of exercise (see table I). Controlling the timing of post-training tests is important to determine if improvements are due to the acute effect of the last bout of exercise or the cumulative effect of exercise training.

2.3 Serum Lipid Outcomes

Fourteen studies examined the effect of HIT on serum lipids (table I). The following measurements of serum lipid metabolism are included in this review: total cholesterol (TC), HDL-C, low-density lipoprotein cholesterol (LDL-C), TG and very low-density lipoprotein cholesterol TG (VLDL-C-TG). Twelve studies examined the effect of HIT on HDL-C, but only one of these studies included participants with low baseline HDL-C.[24] AIT studies of less than 8 weeks and the single SIT study with lipid outcomes reported no change in HDL-C. Of the ten studies that lasted at least 8 weeks, only three demonstrated an increase in serum HDL-C.[18,24,33] Two of these three studies were performed with younger people with normal baseline HDL-C including a 12-week study with adolescents[18] and an 8-week study with young adult men.[33] The third study showed that HDL-C increased in response to 16 weeks AIT performed by middle-aged adults with the metabolic syndrome and very low baseline HDL-C values.[24] None of the nine studies that included a CME arm showed improvement in the HDL-C concentration in the CME group. However, Nybo et al.[15] showed a decrease in the TC : HDL-C ratio in the CME group only, an index reflecting a relative improvement in HDL-C. It is possible that this result was related to the fact that the CME group exercised for 60 minutes/session, but the AIT group only exercised 20 minutes/session. Exercise energy expenditure was not reported in that study and it appears likely that the exercise volume in the CME group exceeded that performed by the AIT group.

There was little or no impact of HIT on the other serum lipid measurements. None of the ten studies examining the effect of HIT on TC showed a decrease in TC using either AIT[15,21,26,33,35-39] or SIT.[29] However, the baseline TC was normal in all but three of the AIT groups,[21,26,37] and therefore the chance for improvement was likely limited. Of the eight studies that included a CME arm,[15,21,26,35-39] only one study showed a decrease in TC in the CME group but not in the AIT group in overweight, middle-aged adults who trained for 12 weeks.[36] None of the four studies that evaluated LDL-C reported changes in response to either AIT or CME programmes,[15,19,26,39] although none of these studies used participants with elevated baseline values. Similar to the findings on LDL-C, none of the ten studies that examined the effect of HIT on TG demonstrated changes in response to AIT[18,19,21,24,26,34,37-39] or with SIT.[29] All of these studies included participants with normal baseline TG values except for one in which mean TG concentration was borderline elevated.[21] Of the eight studies that examined TG that included a CME arm, none showed improvement in TG in either the HIT or the CME group.[19,21,24,26,36-39] In the only study that examined VLDL-C-TG,[34] the fasting concentration of this lipid component decreased in overweight young men after 8 weeks of AIT training.

In summary, HDL-C has been the only serum lipid measurement shown to improve in response to AIT. A minimum duration of 8 weeks was necessary to see improvement in HDL-C, although only three of ten studies that lasted at least 8 weeks showed improvement in HDL-C. The studies that demonstrated improvement in HDL-C were performed with young participants or in participants with very low baseline HDL-C values. None of the studies reviewed reported a beneficial effect of HIT on TC, LDL-C, or TG. It is possible that the duration of the studies was not long enough to observe improvement in serum lipids, as the CME groups in most of the studies did not show any improvement either. These findings are consistent with the scientific literature, which suggests that moderate- or high-intensity aerobic exercise improves HDL-C, but does not frequently improve TC, LDL-C or TG.[41] Furthermore, significant weight loss or change in body composition may be required to achieve improvements in TC, LDL-C, and TG.[42]

2.4 Blood Pressure Outcomes

Twelve studies examined the impact of HIT on blood pressure (table I). Studies of 2- to 10-weeks' duration did not show a change in blood pressure with AIT.[20,26] However, the single SIT study that measured changes in blood pressure did show a transient decrease in systolic blood pressure (SBP) at 24 hours post-exercise that did not persist at 72 hours in ten overweight/obese young men who performed 2 weeks of SIT on a cycle ergometer.[29]

In participants who were not being treated with antihypertensive medication, all five AIT studies of 12- to 16-weeks' duration showed a decrease in blood pressure in a variety of populations. Four of these studies included a CME arm for comparison. A 12-week study of obese, middle-aged adults with baseline elevated diastolic blood pressure (DBP) showed improvement in DBP in both the HIT and CME groups.[37] A 16-week study of middle-aged adults with the metabolic syndrome and baseline elevated SBP/DBP showed improvement in SBP in both the HIT and CME groups, but improvement in DBP in the HIT group only.[24] A 16-week study of young, normotensive females with a family history of hypertension showed improvement in both SBP and DBP in both the HIT and CME groups.[39] A 12-week study of young males with borderline elevated SBP showed improvement in the HIT and the CME group,[15] but only a decrease in DBP for the CME group. Because the baseline DBP in the HIT group was normal in that study, the lack of change in the DBP may not be meaningful. Additionally, the AIT group in that study exercised only 20 minutes, whereas the CME group completed 60 minutes per session, a difference that likely resulted in greater energy expenditure by the CME group. Lastly, a 12-week AIT study of overweight/obese adolescents with borderline elevated SBP showed improvement in both SBP and DBP,[18] but did not include a CME arm for comparison.

All four AIT studies of at least 12-weeks' duration in which there was no change in blood pressure were performed with subjects already being treated with antihypertensive medication.[21-23,40] Three of these studies reported baseline blood pressure measurements.[21,23,40] Because all three studies showed well controlled baseline blood pressure on the antihypertensive medications, the lack of change in blood pressure with exercise training is not unexpected. The study by Guimareas et al.[40] did not show significant changes in either exercise group when the AIT and CME groups were analysed separately, but the authors reported that mean 24-hour DBP and daytime DBP were decreased when the exercise groups were analysed together.[40]

In summary, the available data suggest that measureable improvements in blood pressure can be achieved with AIT training of at least 12-weeks' duration in participants who are not already being treated effectively for hypertension. AIT of at least 12-weeks' duration seems at least as effective as CME in lowering blood pressure in individuals with baseline-elevated measurements, even if training time is less in the AIT arm compared with the CME arm.[15,24,37] No change was observed for those patients who were already being treated effectively for hypertension, but the true impact of HIT on their blood pressure may have been masked by medication.

2.5 Anthropometric Outcomes

Seventeen studies examined the impact of HIT on anthropometric measurements that relate to obesity (table I). The anthropometric measurements included in this review were body weight, BMI, body-fat percentage (BF%), lean body mass percentage, waist-to-hip ratio and waist circumference.

Four of the studies that examined the impact of HIT on anthropometric measurements were performed in participants whose BMI was within the normal range (20–25 kg/m^2); there were no changes in body size or composition in response to exercise training in any of these investigations. These interventions consisted of a 6-week SIT programme in young adults,[14] two AIT programmes of 8- to 16-weeks' duration in young men and women [33,39] and a 12-week AIT programme in older adults with CAD.[21] Three of these studies included a CME arm in which there was also no change in body size or composition.[14,21,39]

Eleven studies measured anthropometric changes in overweight or obese participants. Of the five studies of 2- to 10-weeks' duration,[19,20,26,29,34] only one reported significant changes. In that investigation, waist circumference decreased by 2.4 cm in young obese men who performed SIT for 2 weeks on a cycle ergometer.[29] This reduction in waist circumference seems unexpected after only 2 weeks in a study without a diet intervention and a total exercise time of 2–3 minutes per session for six sessions. In contrast to those shorter studies, the six AIT studies that lasted 3–6 months all showed improvement in anthropometric measurements in response to AIT in a variety of populations. Three AIT studies of 12–16 weeks performed by middle-aged adults on a treadmill demonstrated reductions in BMI and BF%,[37] BMI and waist circumference[24] and BMI, waist circumference, waist-to-hip ratio and BF%.[36,37] Overweight/obese adolescents who performed 12 weeks of AIT on a treadmill experienced a decrease in BMI and BF%.[18] In two studies of adults with CAD, 16 weeks of AIT on a mix of aerobic exercise equipment resulted in decreased body mass,[22] and 6 months of AIT on a cycle ergometer resulted in decreased BMI.[23]

Seven studies with overweight/obese participants had a CME comparison group. The three shorter studies, lasting up to 10 weeks, showed no changes in anthropometric measurements in either the AIT or CME groups.[19,20,26] In comparison, the four studies of 3- to 6-months' duration showed similar improvements in BMI, body mass and/or waist circumference in the AIT and CME groups.[22,24,36,37] The equivalency of anthropometric changes in those studies may be attributable to the fact that total exercise energy expenditure was similar between AIT and CME exercise programmes.[24,37]

Three studies (one SIT and two AIT) examined the impact of HIT on BF%. In MacPherson et al.,[30] young, healthy men and women with baseline BF% of 18–21% who performed 6 weeks of SIT on a treadmill showed a significant reduction in fat mass (1.7 kg), compared with the CME group (0.8 kg). Furthermore, the SIT protocol required only half the time of the CME protocol (6.75 hours/week vs 13.5 hours/week). In Thomas et al.,[38] young men (baseline BF% <20%) and women (baseline BF% <30%) were randomized to perform either 12 weeks of AIT on a treadmill or a volume-matched CME protocol. Both the AIT and CME arms showed similar significant reductions in BF% of ~3%. In a study by Nybo et al.,[15] young men with an initial mean BF% above normal (≥22.3%) who performed AIT or CME on a treadmill for 12 weeks demonstrated a reduction in BF% only in the CME group (1.7% decrease in BF%). This outcome, as noted in prior sections, may be due to the fact that the AIT group appears to have performed less exercise volume than the CME group.

In summary, these results suggest that AIT of at least 12 weeks' duration is likely to induce favourable anthropometric changes in overweight/obese individuals with results similar to CME. Thus, AIT may be a more time-efficient approach to achieve the beneficial effects of exercise on body size and composition. SIT studies with programmes longer than 2 weeks are needed to evaluate the impact of SIT on anthropometric outcomes.

2.6 Mechanistic Considerations

Like the focus of this review, most of the existing HIT investigations have reported the effects of exercise on clinical and functional outcomes.

Some studies, however, have included biochemical and molecular outcomes that have begun to provide mechanistic support for adaptations to HIT that could result in improved physical function. In skeletal muscle, for example, AIT was shown to induce an increase in the transcription factor, peroxisome proliferator-activated receptor γ-coactivator-1α (PGC-1α), which is a master regulator of oxidative phenotype. This increase occurred in patients with obesity, heart failure or the metabolic syndrome,[21,24,37] but was absent in CME comparison groups. An increase in PGC-1α could drive adaptations in mitochondrial biogenesis and glucose transporters that contribute to the increases in $\dot{V}O_{2max}$ and oral glucose tolerance. Similarly, those same studies demonstrated that skeletal muscle sarcoplasmic reticulum calcium uptake was increased by AIT but not CME.[21,24,37] This response is expected to increase the ability to perform high-intensity muscle contractions. Increased abundance of transcripts for PGC-1α, glucose transporter 4 and oxidative pathway genes have been demonstrated in response to acute or short-term SIT; although, to our knowledge, comparisons of these responses to CME have not yet been reported.[14,32,43] In addition to muscle adaptations, changes in cardiac and vascular function in response to HIT have been reported that may account for improvement in $\dot{V}O_{2max}$ and blood pressure. For example, in response to AIT, flow-mediated dilation of the brachial artery, a measure of vascular endothelial function, was increased in obese adults and adolescents and adults with the metabolic syndrome.[18,24,37] This response may result, in part, from the increased nitric oxide availability, as reported in response to AIT but not CME.[24] One SIT study also showed an increase in flow-mediated dilation in healthy adults following 6 weeks of training, although the CME comparison group had a similar improvement.[44] Notably, however, the SIT group performed only 2–3 minutes of exercise per session while the CME group completed 40–60 minutes per session. Therefore, the total exercise volume was not matched in that study. HIT has also been reported to result in an increased cardiac stroke volume in obese women and cardiac failure patients,[21,45] and improved cardiac output in middle-aged adults.[46] Although the picture is still emerging, these initial observations suggest that HIT induces changes in skeletal muscle and the vascular system that could contribute to potentially greater health and functional adaptations compared with CME.

3. Conclusion

Our review and interpretation of the existing literature suggests that SIT and AIT are effective for improving insulin sensitivity and $\dot{V}O_{2max}$, with results equal or superior to CME (table II). In contrast to the rapid and consistent improvements reported for insulin sensitivity and $\dot{V}O_{2max}$ for both SIT and AIT, changes in other cardiometabolic risk factors vary with the type and programme duration of HIT training. AIT studies of at least 12 weeks showed a decrease in BMI or BF% in overweight/obese individuals that was

Table II. Summary of primary cardiometabolic outcomes from high-intensity interval training studies

Major outcomes	Comments
↓ BMI or BF% in overweight/obese: 6/6 AIT studies ≥12 wk	No change in AIT studies <12 wk. One 2 wk SIT study: ↓ WC. Results comparable with outcomes of CME groups
↑ Insulin sensitivity: 3/3 SIT and 4/4 AIT studies	Results comparable with outcomes of CME groups
↑ HDL-C: 3/10 AIT studies ≥8 wk	No change in AIT studies <8 wk. No change in single 2 wk SIT study. 0/9 studies with CME groups showed improvement in HDL-C with CME. Longer intervention may be required to show more consistent improvement with HIT
↓ BP in subjects *NOT* on anti-hypertensive medication: 5/5 AIT studies ≥12 wk	AIT studies <12 wk did not show ↓ in BP. No change with AIT in subjects taking anti-hypertensive medication. Results comparable with CME outcomes
↑ $\dot{V}O_{2max}$: 3/3 SIT and 14/14 AIT studies	Results comparable (5 studies) or superior (8 studies) with all studies that included CME group

AIT = aerobic interval training; **BF%** = body-fat percentage; **BMI** = body mass index; **BP** = blood pressure; **CME** = continuous moderate-intensity exercise; continuous moderate-intensity exercise; **SIT** = sprint interval training; $\dot{V}O_{2max}$ = maximal oxygen uptake as a measure of aerobic exercise capacity; **WC** = waist circumference; ↑ indicates increased; ↓ indicates decreased.

comparable with CME outcomes. AIT studies of at least 12 weeks also demonstrated a decrease in blood pressure in individuals not already being treated with antihypertensive medications, and results were comparable to CME outcomes in individuals with elevated-baseline measurements. HIT has not been shown to induce improvements in serum lipids with the exception of an increase in HDL-C in some AIT trials that lasted at least 8 weeks. Furthermore, CME was not found to be effective in raising HDL-C in any of the nine studies that included a CME arm. Longer study duration may be necessary to show a more consistent increase in HDL-C in response to HIT.

HIT may offer a modest advantage in time efficiency over CME, since many of the beneficial adaptations to exercise can be achieved in ~15–20% less time per typical AIT versus CME exercise session. This is particularly true for $\dot{V}O_{2max}$, since multiple AIT studies showed that AIT exercise sessions requiring 15–20% less time than a matched work volume of CME resulted in equal or greater improvement, compared with CME. Additionally, improvement in $\dot{V}O_{2max}$ was similar to CME results in individuals performing SIT exercise despite 50–90% less exercise time and an apparently large but unquantified difference in energy expended, compared with CME. Furthermore, two other studies where AIT training time was 15% less than CME training time showed equal or superior improvement in the AIT group for several other outcomes, including anthropometric changes, blood pressure, fasting glucose, insulin sensitivity and HDL-C.[24,37] Nybo et al.[15] showed equal improvement in SBP and fasting glucose in groups assigned to AIT and CME even though AIT training time was only one-third as long (20 minutes, with intensity reaching 95% maximal heart rate (HR_{max}) for 5×2 minute intervals), compared with CME training (60 minutes at 80% HR_{max}).

An important concern is the safety of HIT for patients with CAD. SIT has not been studied in this population, but the results from five AIT studies support the premise that supervised AIT is safe in patients with cardiovascular disease, since no training-related adverse events were reported in a total of 72 patients in these five trials conducted for 4 weeks to 6 months.[19-23] Furthermore, in a study by Guiraud et al.,[31] circulating troponin T, a marker of myocardial ischaemia, remained within the normal range in 20 patients with CAD who performed a single session of AIT. Of the four studies performed with CAD patients that also included a CME arm, three showed significantly larger increases in $\dot{V}O_{2max}$ in the HIT group, compared with the CME group.[20-22] For example, older adults with post-infarction heart failure who were randomly assigned to a 12-week AIT programme for 3 days per week on the treadmill had a 46% increase in $\dot{V}O_{2max}$, whereas a CME group matched for exercise energy expenditure demonstrated only a 14% increase in aerobic capacity.[21] Additionally, patients in this study also experienced significant increases in the stroke volume, cardiac output and ejection fraction in the AIT group but not in the CME group. Considering the predictive value of $\dot{V}O_{2max}$ for future cardiovascular events, HIT should be considered as an effective alternative training method for patients with CAD.

For several reasons, HIT may not be appropriate or optimal for everyone. HIT is highly structured and requires at least initial supervision in untrained individuals. Also, HIT may require medical clearance due to the high-intensity nature of the exercise. Although high-impact exercise, such as running on a treadmill may not be an appropriate training method for people with, or at-risk for orthopedic problems, alternatives such as walking on an inclined treadmill or stationary cycling may offer the same benefits without risk of injury. HIT also requires a high degree of motivation to achieve the targeted intensity level and may not be the preferred method of exercise for all people. However, the authors of two studies that compared HIT to CME incidentally noted that participants in the HIT group reported that they found the varying intensities of exercise to be motivating. The participants in the CME group, in contrast, found the exercise training to be quite boring.[21,24] These anecdotal reports suggest that some people may be more likely to adhere to a HIT exercise programme as opposed to a CME programme. Identification of people who may be more likely to adhere to different training styles is an important area of study for future research.

Several strengths and limitations of this review warrant discussion. One of the strengths was that no year limit was applied to the PubMed search criteria. Therefore, studies that met the criteria were retrieved from as early as 1984. Additionally, we included studies using both healthy participants and people with cardiovascular disease or the metabolic syndrome. One of the limitations is that this is not a systematic review with rigorous standards for inclusion/exclusion of potential articles and meta-analytic statistics. However, in our assessment, the HIT literature is not yet extensive enough to perform this type of formal review. The duration of the available studies, type of exercise, selection of outcomes and participant characteristics vary too widely, and many studies have not included a comparison exercise group matched for exercise energy expenditure. Nevertheless, as the current summary demonstrates, there appears to be enough evidence to conclude that HIT is at least as effective as CME for several important health outcomes. Another limitation, that reflects a gap in the literature, is that only five SIT studies were found to have met the criteria for this review, and the longest duration of these was only 6 weeks. Therefore, the true efficacy of SIT on cardiometabolic risk is not yet known and further studies of longer duration are needed before the effects of SIT on clinical outcomes, safety and feasibility can be fully evaluated. Lastly, only one study included adolescents as subjects, and none of the studies included pre-adolescent children. Despite the finding that AIT was shown to produce many of the same cardiometabolic benefits in obese adolescents as shown in adults, further corroboration from paediatric investigations is warranted.

In conclusion, HIT is an effective method of exercise to improve some cardiometabolic risk factors such as BMI, BF%, insulin sensitivity and blood pressure, as well as peak aerobic capacity, as summarized in table II. Additional investigation is needed with people who have low-baseline HDL-C and elevated fasting glucose, to clarify the impact of HIT on these two risk factors. Combining HIT with dietary interventions to assess their separate and combined effects on serum lipids and obesity is another important future area of study. AIT exercise programmes lasting longer than 6 months and SIT programmes of greater than 6 weeks are needed to evaluate the long-term impact of HIT on cardiometabolic risk. Compared with CME, HIT may be a more time-efficient mode of training as vigorous exercise requires less time than CME to achieve the same benefits. The time savings, intensity variation and improved fitness may contribute to increased long-term adherence to an exercise programme for some individuals. Future studies need to address whether compliance and efficacy with HIT is an effective alternative to CME in the real world with a variety of populations for improving fitness and cardiometabolic risk factors.

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