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Maximal Lipid Oxidation (Fat_{max}) in Physical Exercise and Training: A review and Update

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ABSTRACT

The exercise intensity, at which the maximal fat oxidation (MFO) rate occurs, has been defined as Fat_{max}. It has been suggested that the fat oxidation rate during the Fat_{max} intensity is approximately 2-fold greater than at any other intensity although modifiable by several physiological conditions (training, previous exercise or meal). There are a few standardized protocols for estimating of Fat_{max}. The most common tests include: Cycle Ergometer (CE) and Treadmill (TM). Reviewing of tables of the study appoint that the extent of weight or fat loss in response to exercise training varies among individuals.

KEY WORDS: ***Maximal Fat Oxidation, Fatmax, Cycle Ergometer, Treadmill.***

INTRODUCTION

The exercise intensity that causes the highest rate of fat oxidation is referred to as the 'maximal fat oxidation rate' (Fat_{max}) intensity (1). It is possible to reproduce measurements of Fat_{max} using graded exercise calorimetry (2). This approach can be used to predict the quantity of lipid that will be metabolized during exercise. It has been suggested that the fat oxidation rate during the Fat_{max} intensity is approximately 2-fold greater than at any other intensity (3).

Thus, the Fat_{max} intensity is recommended to maximize the beneficial effects of exercise and weight management.

Below 25% of VO_{2max}, fat has been reported to be the major energy supply for the muscle. Above this level, glycogen will rapidly become the predominant fuel, but fat oxidation will still increase until the Lipoxmax/Fat(ox)max is reached. Above this level, it decreases. The reasons for this decrease are not completely understood. Theoretically, lipid supply by lipolysis, lipid entrance in muscle cell, lipid entrance in mitochondria, and mitochondrial fat processing may all be limiting steps. Experiments show that extracellular lipid supply is not limiting, since lipid oxidation decreases even if additional fat is provided to the cell.

Limiting steps seem to be the entrance in mitochondria, governed by CPT-1, which can be inhibited by Malonyl-CoA and lactate (4), and possibly downstream CPT-I other mitochondrial enzymes such as Acyl-CoA synthase and electron transport chain. All these steps are sensitive to the rate of CHO oxidation and thus, a rise in CHO oxidation seems to depress lipid oxidation despite availability of fat and presence of all the enzymes of fat oxidation. Conversely, there is a wide body of evidence that glycogen

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depletion reverses this inhibition and thus increases fat oxidation, as observed during long duration glycogen-depleting exercise.

The maximum fat oxidation rate is defined by genetics, exercise habits, exercise type, degree of obesity and type of obesity (visceral fat or subcutaneous fat). Furthermore, the total fat oxidation rate in terms of exercise (total fat oxidation rate during exercise + post-exercise recovery period) may vary according to exercise intensity, exercise period (length of exercise), meal intake (on an empty stomach or after a meal) and meal content (percentage of fat or carbohydrates in the meal) before the exercise.

Variations in maximum fat oxidation rate, according to the presence of exercise habit and type of exercise, have been reported by the authors (5).

MATERIALS AND METHODS

Measurement of fat oxidation rate

Formulae for the fat oxidation rate and carbohydrate oxidation rate have been created by experimental means for more than 100 years.

Fat oxidation rate (mg/min) = 1.695 × oxygen uptake (l/ min) − 1.701 × carbon dioxide output (l/min)

Carbohydrate oxidation rate (mg/min) = 4.585 × carbon dioxide output (l/min) − 3.226 × oxygen uptake (l/min)

These formulae can be used to ascertain the fat oxidation rate with a device analysing expired gas, or by entering measurements of oxygen uptake and production of carbon dioxide into the formula.

FATMAX test protocol

There are a few standardized protocols for estimating of Fat$_{max}$. The most common tests include: Cycle Ergometer (CE) and Treadmill (TM)

Cycle Ergometer (CE)

For this protocol all participants should complete a FATMAX test (6) during the preliminary trial to establish maximal oxygen uptake (VO_2max). In more detail, the test protocol generally involves a 5 min warm up at 75 W on an electronically braked cycle ergometer. The test started at 95 W, every 3 min the effort increase in incremental steps of 35 W, until voluntary exhaustion reached. During each stage of the test respiratory gas measurements (VO_2 and VCO_2) should be collected using an Gas Analyzer. Test stop if 2 out of the 4 following criteria met. 1) if VO2 do not increase even when workload increase (< 2 mL· kg-1·min-1 increase from the previous stage) 2) a respiratory exchange ratio (RER) of >1.05 3) a heart rate within 10 beats per min of age predicted maximal heart rate 4) a cadence of 50 rpm cannot be maintained. Heart rate (HR) should record during each stage of the test using a HR monitor (Table 1).

Table1. Studies at the Fat$_{max}$ with CE protocol currently available.

	Author	**year**	**Exercise mode**	**subject**	**Fat$_{max}$**	**MFO (maximal fat oxidation) rate**
1	X Chenevie`re et al. (7)	2009	CE	32 healthy volunteers men trained versus an untrained	trained 58.3% VO2max untrained 29.4% VO2max	trained 0.72 g.min-1 untrained 0.32 g.min-1
2	J Achten et al. (6)	2002	CE	18 moderately trained cyclists	61 ±3 VO2max 72 ±2 HRmax	CE$_{average}$: 0.66 ±0.06 g.min-1 CE: 0.69 ± 0.06 g.min-1
3	U Andersson Hall et al. (8)	2015	CE	elite cyclists and triathletes	CON: 55 ± 2 VO2max EXER: 62 ± 1 VO2max FAST: 62 ± 2 VO2max	CON: 0.51 ± 0.04 g.min-1 EXER: 0.89 ± 0.05 g.min-1 FAST: 0.69 ± 0.04 g.min-1 CON : submaximal incremental EXER: two repetitions of 20 min cycling

						and 10 min rowing) at 75% of VO2max. Fast: overnight fast+ submaximal incremental
4	I Croci et al. (9)	2014	CE	24 male recreationally trained : high fatness group low fatness group	Low fatness: 46.7 ± 8.6 VO2ma 65.9 ± 4.9 HRmax High fatness: 45.4 ± 7.2 VO2max 62.2 ± 6.4 HRmax	Low fatness: 0.38 ± 0.19 g.min-1 High fatness: 0.42 ± 0.16 g.min-1
5	EM Støa et al. (10)	2015	CE	9 healthy moderately trained females		High Fat: 0.42±0.14 g.min-1 High CHO: 0.29±0.13 g.min-1
6	MH Suk et al. (11)	2015	CE	T2DM group (12 women) and a control group (12 women).		T2DM group: 0.39 g/min Control:0.58 g/min
7	H Mohebbi et al. (12)	2015	CE	Nine healthy overweight males	-	-
8	K Iwayama et al. (13)	2015	CE	Ten young healthy men	Fat oxidation was maximal at am	
9	F Besnier et al. (14)	2015	CE	136 non-diabetic obese		G1:151.6 ± 36.7 mg/min G2:143.9 ± 38.4 mg/min G3:164.6 ± 50.6 mg/min G1: MFO intensity; G2: 60% of VO2-peak intensity; G3: free moderate-intensity
10	G Jabbour et al. (15)	2014	upright CE	39 pre-pubertal girls 37 pubertal girls	Lipid contribution (mg min^{1} FFM^{1}) 25W: 7.6 50W(3min): 5.6 50W(3min): 5.2 50W(3min): 5.5 75W: 1 In OB pubertal group was highest	
11	S Lanzi et al.(16)	2014	CE	Sixteen L and 16 O men	L (lean): 54% vo$_2$peak O(obese): 42% vo$_2$peak	L (lean): 0.32 g.min-1 O(obese): 0.42 g.min-1
12	I Croci et al. (17)	2014	CE	Fifteen healthy, moderately trained male volunteers		45 g/min at Wmax57.5%
13	J Abildgaard et al. (18)	2013	CE	Forty-one healthy women [premenopausal (*n* = 19), perimenopausal (*n* =8), and postmenopausal (*n* =14)]		Pre: 0.31 0.03 g/min Post:0.21 0.07 g/min
14	S Schwindling et al. (19)	2014	CE	16 male cyclists		endurance trained: 0.32 ± 0.07 g/min highly endurance trained subjects: 0.55 ± 0.22 g/min
15	Tsujimoto et al. (20)	2012	CE	middle-aged obese men	Before weight loose: 34 VO2max after weight loose: 42 VO2max	Before weight loose: 224 mg/min after weight loose: 226.7 mg/min
16	JK Zakrzewski et al. (21)	2012	TM vs CE	22 early pubertal children (9 girls and 13 boys)	Girl: TM 52 VO2peak / 70 HRmax CE 49 VO2peak / 67 HRmax Boy: TM 64 VO2peak/ 79	Girl: TM 217 mg/min CE 176 mg/min Boy: TM 262 mg/min CE 191 mg/min

					HRmax CE 53 VO2peak/ 67 HRmax	
17	S Lanzi et al. (22)	2012	CE	severe obese (SO) men (BMI=40)	Group Fat*max* : 52.6 ± 2.5 VO2max Group HIT: 54.4 ± 2.0 VO2max	Group Fat*max*: 3.8 ± 0.2 mg.kg^{-1}.min^{-1} Group HIT: 4.1 ± 0.2 mg.kg^{-1}.min^{-1}
18	C González - Haro et al. (23)	2011	CE	2 groups of male, well-trained endurance Athletes (short-distance triathletes (ST) and road cyclists (RC)	ST: 52 VO2max RC: 52 VO2max	ST: 0.4 g/min RC: 0.42 g/min
19	CA Rynders et al.(24)	2011	electronically braked bicycle ergometer	A total of 148 untrained adults	-	-
20	Ben Ounis et al. (25)	2011	CE	22 obese children: 12 individuals (six boys and six girls) = trainig and 10 individuals (five boys and five girls) served as controls		Training: Before 135 mgr/min After 235 mgr/min Control: Before 140 mgr/min After 140 mgr/min
21	L Chu et al. (26)	2011	incremental on mechanically braked cycle ergometer	seven obese boys mean age: 11.4 ± 1.0 year		Control:0.16 ± 0.09 g/min Carbo:0.07 ± 0.01 g/min
22	Fabien Pillard et al. (27)	2010	CE	Ten healthy, sedentary, overweight men (age, 27.9 ± 5.6 years. 35, 75% maximal oxygen consumption		Con:0.125 g/min E35:0.28 g/min E70:0.26 g/min
23	K Tolfrey et al. (28)	2010	CE	Twenty-three adolescents (12 girls and 11 boys)	Boys: 39 % VO2peak 61 HR peak Girls: 32 %VO2peak 56% HR peak	Boys: 254 mg/min Girls: 190 mg/min
24	S. Haufe et al. (29)	2010	CE	Obese, otherwise healthy men (n = 38) and women (n = 91)	Men: 37 VO2max Women:39 VO2max	
25	JD Coso et al (30).	2010	CE	endurance-trained (TR) (n=10) and untrained (UNTR) subjects exercising (n=10)	TR: achieved at 60% peak oxygen uptake UNTR: at 40% peak oxygen uptake	TR:0.41 ± 0.01 g/min UNTR:0.28 ± 0.01 g/min
26	S Bordenave et al. (31)	2008	cycle ergometer	Eleven T2D	-	-
27	J Achten et al. (32)	2003	CE	Enduranced trained (55)	62.5± 9.8 VO2max 73± 6.8%HRmax	-

Treadmill (TM)

A standardized protocol should use for all treadmill FATMAX tests. In more detail, the test can start at 5.0 km·h^{-1} and at a gradient of 1% for three min. The speed then increase to 7.5 km·h^{-1}. Speed increase by 1 km·h^{-1} every 3 min until an RER of 1 reached thereafter the speed remain constant and the gradient increase by 1% every 1 min until voluntary exhaustion. Respiratory gas measurements (2 and 2) should collect continuously using a Moxus Modular system. Furthermore, HR should measure throughout the whole test and rating of perceived exertion (RPE) record during each stage (Table 2). The final point of test is similar to the previous protocol (CE).

RESULTS

Lipoxmax values are different and can be modifiable by some factors such as gender (33, 34), puberty (35, 36), Training status (37-39), Obesity (40, 41) and diabetes (42).

Lanzi *et al.* (2014) used Sixteen L (lean) and 16 O (obese) men for their study (16). They reported that subjects (obese men) reached their Fat$_{max}$ point in CE protocol at % 42 VO_{2peak} whereas in Tan *et al.* (2015) study, subjects' s Fat$_{max}$ (Twenty-six obese boys) occurred at %43±11 VO_2max by TM protocol (43). In another study twelve women with T2DM when reached their Fat$_{max}$ by CE protocol, their MFO rate was about 0.29 g/ min (11) while A Cataldo *et al.* (2014) reported that individuals in their study (Fifteen sedentary T2D patients) showed 6.71±0.46 mL/kg/min (MFO rate) at their Fat$_{max}$ point (44).

As well as in Coso *et al.* (2010) study subjects (endurance-trained) achieved at 60% peak oxygen uptake at their Fat$_{max}$ point with a CE protocol (30) whereas in another study when endurance trained individuals reached their Fat$_{max}$ point with a CE protocol , their VO2max was about 62.5± 9.8 (32) and also Rami *et al.* (2014) when used a TM protocol for their subjects (Active male students), they observed that subjects achieved their Fat$_{max}$ when their VO_{2max} was about 40.09±2.58 (45).

Table2: Studies at the Lipoxmax with TM protocol currently available.

	Author	year	Exercise mode	subject	Fatmax	MFO (maximal fat oxidation) rate
1	J Zakrzewski et al. (46)	2012	TM	12 OW and 15 NO girls	Over Weight : 52 ± 10 VO2max non Over Weight :63 ±12 VO2max	-
2	M Rami et al. (45)	2014	TM	Active male students sedentary male students	Active :40.09±2.58 VO2max 56.45±4.33 HRmax Sedentary: 42.72±3.01 VO2max 60.09±3.37 HRmax	$0.29±0.03\ g.min^{-1}$ $0.23±0.02\ g.min^{-1}$
3	MC. Venables et al. (39)	2005	TM	300 healthy men and women	48.3 ± 0.9 VO2max 61.5 ± 0.6% HRmax	7.8 _ 0.13 $(FFM)^{-1}$ _min^{-1}
4	S Takagi et al. (47)	2014	TM	healthy young men	43.2 ± 5.7%VO2peak	0.65 ± 0.12 g.min-1
5	M Rami et al. (48)	2012	TM	9 untrained male	42 ±3 VO2max 58±2 HRmax	0.23 g.min-1
6	NA Crisp et al. (49)	2012	TM	overweight boys (8–12 years)	58±2 VO2max	0.44 g.min-1
7	A Mousavian et al. (50)	2013	TM	untrained female university students	Morning: 40.92±6.17 g/m Afternoon: 55.83±3.55 g/m Night: 57.19±3.11 g/m	Morning: 0.30±0.051 Afternoon: 0.45±0.082 Night: 0.44±0.10
8	H Darvakh et al. (51)	2014	TM	4Tnon4T9T-athletes9T male students	Morning: 14.92±41.17 ml/kg/m Afternoon 13.83±57.55 ml/kg/m Night: 10.99±56.96 ml/kg/m	Morning:0.056±0.17 g.min-1 Afternoon: 0.53±0.17 Night: 0.037±0.26
9	M Konishi et al.(52)	2013	TM	healthy young males	18.7 ± 0.8 ml/kg/m	
10	K Iwayama et al. (53)	2015	TM	Nine young male endurance athletes	Maxmal :5.5 kcal/min At 7-7.5 am	
11	SL Robinson et al. (54)	2015	TM	53 young, healthy men	MFO (g/min) was significantly and positively correlated with 24 h fat oxidation (24 h FO, g/d),	
12	S Tan et al. (43)	2015	TM	Twenty-six obese boys and 20 lean boys	Obese boys: Control: 41±10 VO2max Exercise: 43±11 VO2max Lean boys: Control: 52±13 VO2max Exercise: 49±19 VO2max	Obese boys: Control: 0.41±0.18 g/min Exercise: 0.38±0.13 g/min Lean boys: Control: 0.29±0.12 g/min Exercise: 0.32±0.17 g/min
13	J Wang et al. (55)	2015	A graded treadmill walkingerunning test	Thirty women		Contorl: Rest:0.10 ± 0.04 4km/h: 0.32 ± 0.10 5km/h: 0.18 ± 0.20 Exercise:

						Rest: 0.07 ± 0.03 4km/h: 0.32 ± 0.11 5km/h: 0.28 ± 0.08
14	A Cataldo et al. (44)	2014	TM	Fifteen sedentary T2D patients (9 males, 6 females) fifteen healthy sedentary subjects	T2D patients: 70±1.27 mL/kg/min Healthy: 64±2.61 mL/kg/min	T2D patients: 6.71±0.46 mL/kg/min Healthy: 7.19±0.77 mL/kg/min
15	S Tan et al. (56)	2014	A graded TM	Thirty women (45–59 years	Exercise : Before: 52 ±6 After: 48 ±8 Control: Before: 52 ± 13 After: 57 ± 10	Exercise : Before: 0.38 ± 0.07 After: 0.45 ± 0.08 Control: Before: 0.40 ± 0.09 After: 0.41 ± 0.09
16	AN Blaize et al. (57)	2014	TM	Fourteen active, healthy women divided into 2 groups (15–24.9% = lower-fat group; 25–35%= higher-fat group).	Lower-fat group: 52% VO2max higher-fat group:49 %VO2max	Lower-fat group: 0.39 6 0.1 g.min-1 higher-fat group: 0.49 6 0.1 g.min-1
17	AE Lima-Silva et al. (58)	2010	incremental TM	18 runners	Low performance: 68.7 VO2max Moderate performance: 59.9 VO2max	Low performance: 0.27g/min Moderate performance: 0.47 g/min
18	F. Scharhag-Rosenberger et al. (59)	2010	TM	17 sedentary participants	0: 35 ± 6 VO2max 6: 44 ± 15 VO2max 12: 50 ± 14 VO2max	0: 0.26 ± 0.10 g/min 6: 0.27 ± 0.08 g/min 12: 0.33 ± 0.12 g/min
19	X Chenevière et al. (60)	2009	Incremental TM	Twenty moderately trained subjects (9 men and 11 women). incremental test (IncrC) graded test on a treadmill (Incr)	IncrC: 70.7 ± 2.7 VO2max Incr: 65.5 ± 2.6 VO2max	IncrC: 0.50 ± 0.03 g/min Incr: 0.40 ± 0.03 g/min

Table 3: Studies at the Lipoxmax with other protocol currently available.

	Author	**year**	**Exercise mode**	**subject**	**Fatmax**	**MFO (maximal fat oxidation) rate**
1	S S Ferreira et al. (61)	2013	Walking Test	adult women	51.3 ± 7.2 VO2max	0.303 g.min-1
2	LAG Freitas et al. (62)	2015	Walking	12 obese women	self-selected exercise intensity 62.0 ± 10.2 VO2max imposed exercise intensity 49.2 ± 5.2 VO2max	0.372 ± 0.08 0.490 ± 0.1
3	RDS Silveira et al. (63)	2016	running protocols	Sixteen recreational athletes Males (n = 9) Females (n = 7)	-	Fat peak test 1:0.52 g.min-1 Fat peak test 2: 0.49 g.min-1 48 to 72 h later than test 1
4	S Alkahtani et al. (64)	2014	The 30-min MIIT involved 5-min repetitions of workloads 20% below and 20% above the MFO intensity.	Twelve sedentary obese males	-	MIIT : 0.17 g.min-1 GXT:0.14 g.min-1
5	E Makni et al. (65)	2012	six-minute walking distance (6MWD) - cycle ergometer = for fatmax	131 school-aged obese children, 68 boys and 63 girls	-	Boy: 126.5±12.1 ng min^{-1} Girl: 120.7±10.0 ng min^{-1}

CONCLUSION

Nowadays the most important question for population that wants to lose weight is what is the easiest and fastest method to lose the maximum weight. Fat_{max} may be is an efficient exercise intensity for weight loss programs, health-related exercise programs, and endurance training. Several authors assume that ‘‘fat loss depends on energy deficit only, independently of the method for weight loss’’ (66). Studies clearly indicate that is quite possible to lose fat while preserving fat-free mass through regular prolonged exercise of moderate intensity and if energy intake is kept constant at baseline level (67). They also confirm the importance of the individual differences in response to negative energy balance. It is well appointed that the extent of weight or fat loss in response to exercise training varies among individuals (68-70). Future research should investigate an exercise test with which Fat_{max} can be accurately determined, and such a test needs to be validated and tested for reliability.

APPLICABLE REMARKS

- We have defined the exercise intensity at which maximal fat oxidation is observed as Fat_{max}.
- Fat_{max} may have importance role for weight loss programs, and health-related exercise Programs.
- $Lipox_{max}$ values are different and can be modifiable by some factors such as gender, puberty, training status, obesity and diabetes.

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