The Kinetics of Cardiopulmonary Dynamics during Recovery Following Maximal Exercise

S. Mukhopadhyay Ph.D.[1] , Sukhjinder M.Sc.[2], L.S. Sidhu Ph.D.[3] and S.K. Verma Ph.D.[4]

[1]Head, Department of Exercise Physiology, SAI, National Institute of Sports, Patiala, [suman_nis@yahoo.com]
[2]Research Fellow Department of Exercise Physiology, SAI, National Institute of Sports, Patiala
[3] Ex-Professor, Department of Human Biology, Punjabi University, Patiala
[4]Professor, Department of Physiotherapy and Sports Science, Punjabi University, Patiala
[satishsk1@rediffmail.com]

Abstract

The study was carried on 193 elite male sports person consisting of (a) Anaerobic group (n =43), (b) Mixed group (n=100): This group was further divided into two sub - groups i) Non-Combative (n=60) ii) Combative (n =40), (c) Aerobic group (n =50). Graded cardiopulmonary exercise testing was carried out till exhaustion and the selected cardiopulmonary transients were recorded every 15 seconds by a portable computerised metabolic analyzer for the entire duration of test and recovery. The results revealed that the long distance athletes (aerobic group) had significantly different recovery patterns so far as the oxygen uptake during recovery was concerned, and they were also found to posses the highest VO_2 max were able to recover much quicker than those who didn't ($P<0.01$). Further, the cardiopulmonary dynamics during recovery was found to be influenced by training. The study concluded that a strong emphasis needs to be given to adequately develop the aerobic component in games and sports where recovery is important, even in anaerobic sports.

Key Words: **VO_2 max, HR_{max}, VE_{max}, VCO_2, Anaerobic threshold**

Introduction:

The return of the muscle homeostasis to its pre-exercise state following exercise is known as recovery *(Tomlin and Wenger, 2001).* The process of recovery from exercise is perhaps just as important as exercise itself and the energy process at work during recovery from exercise are just as crucial as those at work during exercise.

A strong relationship between aerobic fitness and recovery from high intensity intermittent exercise has already been established *(Tomlin and Wenger, 2001);* although such a relationship following a graded maximal exercise is yet to be demonstrated. Further, it is also conjectured that a high level of aerobic fitness is a prerequisite even for superior performance in anaerobic sports *(Aziz et al, 2000)*, since phosphocreatine resynthesis has been found to be dependent on the availability of oxygen during recovery *(Harris et al, 1976).* It is therefore reasonable to assume that an individual with a higher VO_2 max will posses a greater capacity to deliver oxygen to the working muscle, which in turn will lead to a greater and quicker rephosphorylation of CP stores during recovery periods *(Balsom et al, 1994). Dawson et al, 1993*, also reported significant correlation between VO_2 max and anaerobic performance.

If an enhanced oxygen uptake does indeed facilitate recovery, it is pertinent and reasonable to hypothesize that the recovery patterns of the various cardiopulmonary transients will vary in athletes, depending on the volume of aerobic training a particular group of athletes might undertake.

Thus the purpose of our study was to decipher the dynamics of pattern of recovery as an indicator of specificity of events and to find out the possible differences in kinetics of cardiopulmonary adjustments during recovery and to correlate it with the functional status of sports persons.

Materials and Methods:

Subjects: The study was conducted on 193 volunteers, all elite sports persons, consisting of a minimum of 40 in each of the four groups mentioned below, in which the athletes have been categorized. The volunteers were taken from elite male sports persons belonging to various National camps that were held in the Sports Authority of India, Netaji Subhas National Institute of Sports, Patiala. All volunteers were adults, within the age range of 18 to 26 years. The volunteers were divided into three groups, based on their game/event, and the energy system that predominantly caters to their metabolic needs, as under:

***Anaerobic group** (n=43):* This included volunteers of events of athletics (n=33) [belonging to sprints (n=12), and jumps (n=21)], and weight lifting (n=10).

Mixed group (n=100): This group was further subdivided into two sub-groups:

(i) *Mixed Group Non-Combative* (n=60), including volunteers of events of middle distance running (800 m and 1500 m; n=21), Table tennis (n=9), Volleyball (n=14) and Rowing (n=16), and,

(ii) *Mixed Group Combative* (n=40**)**, including volunteers of events of combat events/contact sports, consisting of Kabaddi (n=12), Judo (n=14), and Boxing (n=14).

Aerobic group (n=50): This included volunteers of events of long distance running (3000 m and above: n=50).

Each volunteer was first subjected to a physical examination that included measurement and / or recording of the following:

Date of Birth (from which the decimal age was calculated)

Stature (height in cm)

Weight (in kg)

Body Surface Area (BSA: in sq.m; *Dubois, 1916*)

Subsequent to the above, each volunteer was explained in detail as to what he was required to do and the efficacy of carrying out the CPET. Only those volunteers participated in the study who were willing, and prior verbal consent was obtained from each of them. Thereafter, the volunteers were subjected to CPET to assess their following physiological measures:

VO_2 (oxygen consumption: L/min and ml/kg/min)

VCO_2 (carbon dioxide production: L/min and ml/kg/min)

VE (pulmonary ventilation: L/min)

HR (heart rate: beats/min)

TV (tidal volume: ml)

f_R **(**frequency of respiration: No. of expirations/min**)**

O_2 Pulse (oxygen consumption / heart rate: ml)

Methods:

Exercise tests were performed on an electronically operated motor driven treadmill (LE 6000: Erich Jaeger, Germany), using a test protocol consisting of administration of a graded running. The initial speed was prefixed at 8 km/h and this was increased every two minutes at the rate of 2 km/h, till exhaustion *(Leger and Boucher, 1980)*, consequent to which, the volunteers were asked to walk briskly at a recovery speed of 6 km/h. The peak treadmill running speed or the maximal velocity attained, that could be maintained for a whole minute during the test was taken as the 'velocity at VO_2 max' or vVO_2 max. If an athlete failed to sustain 60 seconds at his peak speed, the velocity of the immediately preceding completed work stage (treadmill speed) was recorded as his velocity at the VO_2 max or the vVO_2 max *(Noakes et al, 1990)*. The tests were carried out in an air conditioned room with temperature and humidity levels controlled at 23° $\pm$ 2° C and 55 $\pm$ 5% respectively. The tests were carried out at least 3h after last meal and after a minimum of 12h of limited exertion.

All measurements were carried out breath-by-breath, using the computerized metabolic analyzer, "Oxycon Champion", (Erich Jaeger, Germany). The heart rate (HR) and ECG were continuously monitored during the period of test and recovery. The volunteers breathed through a small dead space (35 ml), low resistance mouthpiece and TripleV volume transducer. Respired gases were withdrawn automatically from the mouthpiece and passed on to the CO_2 and O_2 analyzers for breath-by- breath display and recording of the various physiological variables. Temperature and pressure sensors of the instrument automatically read the ambient temperature and atmospheric pressure, and data about existing relative humidity was fed to it. All gas volumes were automatically corrected for, and expressed in STPD, and V_E was expressed as V_E BTPS.

The CO_2 and O_2 analyzers, as well as the volume transducer were calibrated before each test using a precision gas mixture (5% CO_2; balance N_2), and a 2 litre calibration pump (both Erich Jaeger, Germany).

A test was considered maximal only if a change in load did not produce a corresponding significant change in HR and VO_2 ($\pm$ 4 bpm and 100 ml respectively), and if the HR values are within 15% of the age - predicted HRmax *(Bruce et al., 1974; Jones et al., 1985)*. The RQ was greater than 1.13 also *(Inbar et al., 1994)*. The Anaerobic Threshold (AT) point was determined from the deviation point of the V_E-$V0_2$ linearity *(Beaver et al., 1985)*, and confirmed from plots of VCO_2 vs. VO_2 (modified V-slope technique, Sue et al., 1988). The VO_2, measured at the anaerobic threshold (AT) level was taken as the AT-VO_2. Similarly, the other cardiopulmonary transients measured at the maximum of exercise, for example, VE, HR, etc. were suffixed with the word 'max', like V_E max and HRmax, and their values obtained at the anaerobic threshold level were prefixed with AT, like, AT-V_E and AT-HR.

The breath-by-breath data of the aforementioned cardiopulmonary transients were converted to 10 second averaged data, by the analysis software, and all 10 sec data of the cardiopulmonary transients beyond their maximal effort, during the first 5 minutes of recovery was computed for comparisons.

Statistical Analysis:

The means and standard deviations of the physical characteristics of decimal age, height, weight and body surface area were calculated by the statistical packages of the Microsoft Office (MS 6.0) / MS Excel. The 10 second averaged breath-by-breath data of HR, VE, VO_2 and VCO_2 responses for each athlete during the entire 5 minutes of recovery were tabulated, based on the discipline/event of the athlete.

Individual regression equations for the slope of responses were then drawn for each athlete, for each of the cardiopulmonary transient. The coefficient of regression (r) values thus obtained were tabulated and one way single factor ANOVA was applied to study if and whether the slopes are significantly different. In all cases where the differences were found to be significant ('F' value higher than the 'critical F'); Duncan's Multiple Range (Post-Hoc) Tests were carried out to elucidate the degree of significance between the groups.

Results and Discussion:

Table 1: Comparison of means (±SD) of physical profiles and exercise duration of athletes of Anaerobic, Mixed Non-Combat, Combat and Aerobic Group

Event	(n)	Dec. Age (yrs)	Height (cm)	Weight (kg)	BSA (sqm)	Total Exercise Duration (minutes)	AT-Time (minutes)	Supra-AT Time (minutes)
Anaerobic Group (Total)	43	21.4 (2.66)	174.2 (7.73)	69.2 (13.17)	1.83 (0.17)	11.2 (2.46) [11:12.0]	6.9 (1.94) [6:54.0]	4.2 (1.33) [4:12.0]
Mixed Non-Combat Group (Total)	60	21.6 (2.86)	177.6 (10.49)	66.6 (9.91)	1.83 (0.18)	12.56 (2.88) [12:33.6]	8.08 (2.41) [8:4.8]	4.5 (1.48) [4:29.4]
Mixed Combat Group (Total)	40	22.0 (2.71)	172.1 (6.83)	68.1 (9.62)	1.80 (0.15)	10.12 (1.96) [10:07.2]	7.20 (1.75) [7:12.0]	2.92 (0.85) [2:55.2]
Aerobic Group (Total)	50	20.7 (2.97)	169.3 (5.53)	56.6 (7.92)	1.65 (0.13)	16.7 (3.58) [16:42.0]	10.9 (2.24) [10:54.0]	5.8 (2.47) [5:48.0]
Grand Total	193	21.1 (2.87)	173.5 (8.62)	64.9 (11.31)	1.78 (0.18)	12.84 (3.74) [12:50.4]	8.36 (2.65) [8:21.6]	4.43 (1.94) [4:25.8]

Table 1 compared the means (±SD) of the physical profile and the exercise duration of all the four different groups of athletes, the anaerobic group, the mixed non-combat group, the mixed combat group and the aerobic (long distance) group. Table 1 revealed that the differences in ages between the groups of athletes were not significant. The anaerobic group was found to be significantly taller than the aerobic group ($p<0.01$). The mixed non-combat group was significantly taller than the mixed combat group ($p<0.01$) and the aerobic group ($P<0.01$). The mixed combat group was also found to be significantly taller than the aerobic group ($p<0.05$). Table 1 also revealed that the anaerobic and aerobic groups differed significantly ($p<0.01$), in their weights. The aerobic group was also significantly lighter than both the mixed non-combat and combat groups ($p<0.01$). The BSA of the aerobic group was significantly lesser than the anaerobic, mixed non-combat and the mixed combat groups ($p<0.01$). It is already an established fact that the distance runners are usually the shortest and the lightest, which is exhibited in our study also. The total exercise time of the aerobic group was found to be significantly higher than the anaerobic, mixed non-combat and the mixed combat groups ($p<0.01$). The anaerobic group exercised for a significantly ($p<0.05$) longer period than the mixed combat group and significantly shorter than the mixed non-combat group ($p<0.05$) and the aerobic group ($p<0.01$). The exercise duration of the mixed non-combat group was also significantly higher than the mixed combat group ($p<0.05$). The time to reach the anaerobic threshold level, or the AT-Time was significantly longer for the aerobic group than the three other groups ($p<0.01$). The AT-Time of the anaerobic group was also significantly lesser than the mixed non-combat group ($p<0.01$). The mixed non-combat group had significantly longer AT-Time than the mixed combat group ($p<0.05$). The time spent beyond the anaerobic threshold level, or the Supra-AT Time for the aerobic group athletes was higher than all the other three groups ($p<0.01$). Whereas there were no significant differences observed between the anaerobic and the mixed non-combat group, the anaerobic group's AT-Time was significantly longer than the mixed combat group ($p<0.01$). The results indicate that the mixed combat group are not able to sustain a high degree of anaerobiosis, as a group and as well as, there exists very little differences between the anaerobic and mixed non-combat group athletes, in physical perspectives. The results also reveals that the aerobic group athletes displays not only the longest duration of exercise, corresponding to a mean vVO_2 max of 22 km/hr, but they are also able to tolerate the highest degree of anaerobiosis, since that are able to sustain for the longest duration at the supra-threshold level of exercise. This indicates that aerobic training possibly can influence the duration of exercise that can be tolerated at the supra-threshold level.

Table 2: Comparison of means (±SD) of some selected cardiopulmonary transients of athletes of Anaerobic, Mixed Non-Combat, Combat and Aerobic Group.

Event	(n)	HR max (bpm)	AT-HR (bpm)	VO_2 max (ml/kg/min)	AT-VO_2 (ml/kg/min)	AT-VO_2 max%	V_E max (L/min)	AT-V_E (L/min)
Anaerobic Group (Total)	43	183 (8.59)	155 (9.83)	54.8 (10.52)	42.2 (10.81)	74.3 (11.06)	129.8 (27.60)	72.2 (19.67)
Mixed Non-Combat Group (Total)	60	181 (1.48)	160 (7.98)	59.8 (12.35)	45.9 (12.76)	77.2 (9.90)	135.0 (22.19)	81.04 (18.88)
Mixed Combat Group (Total)	40	180 (7.18)	159 (7.16)	54.8 (10.74)	44.5 (11.16)	80.7 (8.59)	131.0 (20.28)	87.3 (20.71)
Aerobic Group (Total)	50	180 (5.97)	156 (6.51)	74.9 (10.02)	64.8 (9.01)	83.0 (5.16)	132.4 (20.77)	82.9 (13.80)
Grand Total	193	181 (8.19)	158 (8.16)	61.1 (13.88)	49.1 (14.63)	78.8 (9.45)	132.3 (22.71)	80.8 (18.88)

Table 2 compared the cardiopulmonary responses of all the four groups. The Table illustrates that the maximum heart rate was not found to be significantly different amongst the groups. The AT-HR values of the aerobic group was not found to be significantly different from the anaerobic group, but was different from the mixed non-combat and mixed combat groups at $p<0.01$ and $p<0.05$, respectively. The anaerobic group AT-HR was also found to be significantly different from the mixed non-combat and mixed combat groups at $p<0.01$ and $p<0.05$, respectively. The VO_2 max and AT-VO_2 values of the aerobic group were found to be significantly higher than those of the other three groups ($p<0.01$).

Differences between the VO_2 max values of the mixed non-combat and the mixed combat groups were also significant at $p<0.05$. The other AT-VO_2 values were not found to be significantly different. The fractional utilization of VO_2 max at the AT level, or AT-VO_2max% of the aerobic and the mixed combat group was found to be significantly different at $p<0.05$. The AT-VO_2max% values of the anaerobic group was significantly different from the mixed combat group at $p<0.01$. Values of the other groups were not significantly different from each other.

The V_E max was not found to be significantly different between the groups. The AT-V_E values of the anaerobic group was however significantly different with the values of the aerobic group ($p<0.01$), mixed non-combat ($p<0.05$) and mixed combat ($p<0.01$) groups.

Comparison of Kinetics of VO_2 responses

The slopes of the kinetics of VO_2 during recovery demonstrated that the aerobic group had oxygen uptake slopes that were significantly different from all the three other groups. The VO_2 consumption patterns of the aerobic (long distance athletes) group had the steepest slope, distinctly and significantly different from those of the three other groups. Since this group of athletes was also found to be endowed with the highest oxygen uptake capacity (Table 1), it would be pertinent to suggest that endurance training and/or a higher VO_2 max does result in superior recovery. It has already been established that individuals with high maximal aerobic capacity exhibit increased concentrations of aerobic enzymes, increased mitochondrial number, size and surface area and increased myoglobin all contributing to improved oxygen extraction by muscle. In conjecture with enhanced ATP/CP stores and elevated myokinase and creatine kinase concentration in trained athletes, results in supplying more energy through the phosphagen system and aerobic system, thus decreasing reliance on anaerobic glycolysis, which too, could influence the VO_2 recovery patterns.

Comparison of Kinetics of HR responses

It is reported by many investigators that the magnitude of work done determines the rate of decrease of heart rate during recovery and the recovery heart rate at the beginning of recovery is strongly influenced by the heart rate during work and VO_2 max but the influence of these parameters on recovery heart rate decreases as the recovery progress.

In our study it was shown that the kinetics of Heart rate responses of the different groups during recovery were not found to be significantly different from each other. Similarity of HR dynamics during recovery possibly cannot be entrained and that training possibly is not able to modify the HR response pattern or its slope.

Comparison of Kinetics of V_E responses

The kinetics of pulmonary dynamics during recovery was not found to be significantly different between the groups also. The existence of non-significant differences between the various groups suggests that the underlying control mechanisms of the V_E response dynamics function in a similar manner in athletes irrespective of the type of training, during recovery, varying only barely and marginally, in the case of aerobic group athletes. Ventilation has been found to increase monoexponentially, with a time constant which is about 10% slower than that of VCO_2 *(Casaburi et al, 1989; Whipp et al, 1982).* It has been suggested that there may be a control link between V_E and VCO_2 (*Wasserman et al, 1977 and Whipp, 1981).*

Comparison of Kinetics of VCO_2 responses

The dynamics of VO_2 responses during recovery revealed that the slope response of the anaerobic group was significantly different from the aerobic group and the mixed non-combat groups. The kinetics of VCO_2 recovery responses of the mixed combat group did not differ significantly from any of the other groups.

The comparison of the VCO_2 responses revealed the general trend wherein the aerobic group consistently displayed response kinetics distinctly different from the three other groups. The VCO_2 kinetics, unlike VO_2 , appears not to be controlled but rather reflect the time course with which CO_2 is produced metabolically and stored in tissues. The difference in VO_2 and VCO_2 response is therefore presumably a reflection of the amount of intramuscular storage *(Whipp and Ward, 1990).*

However the present study indicates that the slope response of VCO_2 responses during recovery may be guided by the degree of anaerobiosis or CO_2 production during the exercise, and may not be related to the initial storage, as observed by (*Whipp and Ward, 1990).*

Table 3: Comparison of oxygen consumption (VO_2) during the recovery in different groups of athletes

ANOVA: Single Factor:

Summary

	ANOVA						
	Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Recovery VO_2	Between Groups	0.01599	3	0.00533	4.943567	0.00251	2.652392
	Within Groups	0.20379	189	0.00108			
	Total	0.21978	192				
Recovery Heart rate	Between Groups	1.856729	3	0.61891	0.602585	0.614089	2.652648
	Within Groups	193.0931	188	1.027091			
	Total	194.9498	191				
Recovery Ventilation	Between Groups	1.022662	3	0.340887	0.201804	0.895049	2.652392
	Within Groups	319.2594	189	1.689203			
	Total	320.2821	192				
Recovery VCO_2	Between Groups	0.007146	3	0.002382	2.772614	0.042791	2.652392
	Within Groups	0.162375	189	0.000859			
	Total	0.169521	192				

Conclusions:

The study entitled, 'The Kinetics of Cardiopulmonary Dynamics During Recovery following Maximum Exercise in selected groups of elite Indian Athletes', is one of the first of its kind in our endeavour for the enhancement of knowledge and understanding of the complex cardiopulmonary physiology of athletes during recovery.

This study elucidated the actual kinetics of the dynamics of the change in the metabolic transients during recovery, in the elite athletes of India, which can be used as pointers for the evolution of credible training programmes, in the pursuit of enhancement of, and excellence in performance. The major findings and conclusions are enumerated below:

The kinetics of VO_2 during recovery showed that the aerobic group had O_2 uptake slopes which were significantly different from the three other groups. The results indicated that the factors controlling or influencing the oxygen uptake possibly cannot be entrained by physical activity at least so far as the rate of uptake is concerned, although, the aerobic groups in this study quantitatively consumed the highest amount of Oxygen, significantly so, from the other groups, yet its kinetics or rate of uptake was similar to those of the other groups. The fact that the aerobic group had significantly different recovery responses strongly suggests that the oxygen uptake kinetics during recovery is guided predominantly by the oxygen debt (or the excess post exercise oxygen consumption) contracted during the exercise, or the degree of anaerobiosis tolerated. Clearly, since the aerobic group tolerated the greatest anaerobiosis, they exhibited the highest and quickest oxygen uptake. The positive effects of aerobic training therefore, cannot be ruled out in enhancing the VO_2 kinetics during recovery in the aerobic group athletes.

Since increases in VO_2 max and aerobic capacity results from endurance training, aerobic capacity measures have proven useful in predicting success in distance running events *(Costill, 1973 and Tanaka, 1984)*. Aerobic group has a different recovery pattern because with aerobic training concentrations of aerobic enzymes increases, mitochondrial number, size and surface area and myoglobin content increases all contributing to improved oxygen extraction by muscle *(Saltin, 1980 and Holloszy, 1984).* Aerobic training also results in increased muscle blood flow, which is accomplished through elevated cardiac output, increased capillarisation of muscle tissue and an improved ability to vasodilate. Oxygen delivery in the endurance trained athlete is further improved by increases in blood volume and total hemoglobin volume. Together these enhancements results in an increased rate of VO_2 during high intensity exercise and decreased time to reach peak VO_2 during exercise. Moreover, the enhanced ATP/PCr stores and elevated myokinase and creatine concentration, results in an ability to supply more energy through the phosphagen and aerobic systems, thus decreasing the reliance on anaerobic glycolysis. With reduced anaerobic glycolysis during exercise, less energy is required during the recovery period to rid the muscle of H^+ and lactate, potentially hastening the recovery process.

Other training effect seen in aerobically trained individuals may improve temperature regulation during and after exercise (Baum et al, 1976). Thus it appears that the metabolic and circulatory adaptations associated with high levels of aerobic power should facilitate faster recovery from high intensity exercise.

Comparisons of the kinetics of the HR responses during CPET revealed that there were no differences in the kinetics of the HR responses of all the four different groups during recovery, strongly suggesting that the control mechanisms of such dynamics may not be entrained by training. The kinetics of pulmonary dynamics during recovery was not found to be significantly different between the groups.

References:

1. Aziz, A.R., China, M. and The, K.C. (2000): The relationship between maximal oxygen uptake and repeated sprint performance indices in field hockey and soccer players. *J. Sports Med. Phys. Fitness,* 40: 195-200.
2. Balsom, P.D., Ekblom, B., Gaintanos, G.C. et al. (1994): Reduced oxygen availability during high intensity intermittent exercise impairs performance. *Acta Physiol. Scand*., 152: 279-285.
3. Baum, E., Frusk, K., Schwennick, H.P. (1976): Adaptive modifications in the thermoregulatory system of long-distance runners. *J. Appl. Physiol*., 40 (3): 404 - 410.
4. Beaver, W.L., Wasserman, K. and Whipp, B.J. (1986): A new method for detecting anaerobic threshold by gas exchange. *J. Appl. Physiol*., 60: 2020-2027.
5. Bruce, R. A., Gey (Jr.), G. O., Cooper, M. N., Fisher, L. D. and Peterson, D. A. (1974): Seattle heart watch: Initial clinical, circulatory and electrocardiographic responses to maximal exercise. *Am. J. Cardiol*.., 33: 459 - 565.
6. Casaburi, R., Cooper, C., Effros, R. M. and Wasserman, K. (1989): Time course of mixed venous O_2 saturation following various modes of exercise transition. *Fed. Proc*., 3: A849.
7. Costill D, Thomason H. Roberts E. (1973): Fractional utilization of the aerobic capacity during distance running. *Med. Sci. Sports Exerc*., 5: 248-252.
8. Dawson, B., Fitzsimons, M. and Ward, D. (1993): The relationship of repeated sprinting ability to aerobic power and performance measures of anaerobic capacity and power. *Aust. J. Sci. Med. and Sport*, 25: 88-93.
9. Harris, R.C., Edwards, R.H.T., Hultman, E. et al. (1976): The time course of phosphorylcreatine resynthesis during recovery of the quadriceps muscle in man. *Pflugers Arch*., 367: 137-142.
10. Holloszy, J.O. Coyle, E.F. (1984): Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *J. Appl. Physiol*., 56: 831-838.
11. Inbar, O., Oren, A., Scheinowitz, M., Rotstein, A., Dlin, R. and Casabury R. (1994): Normal cardiopulmonary responses during incremental exercise in 20- to 70-yr-old men. *Med. Sci. Sports Exerc*., 26. (5): 538 - 546.
12. Jones, N. L., Makrides, L., Hitchcock, C., Chypchar, T. and McCartney, N. (1985): Normal standards for an incremental progressive cycle ergometer test. *Am. Rev. Respir. Dis.,* 131: 700 - 708.
13. Leger, L. and Boucher, R. (1980) : An indirect continuous running multistage field test. The Universite de Montreal track test. Can. J. Appl. Sports Sci., 5: 77 - 84.
14. Noakes, T. D., Myburgh, K. H. and Schall, R. (1990): Peak treadmill running velocity during the VO2 max test predicts running performance. J. Sports Sci., 8: 35 - 45.
15. Saltin B, Rowell, l.B. (1980): Functional adaptation to physical activity and inactivity. Fed Proc., 39: 1506-1513.
16. Sue, D.Y., Wasserman, K., Moricca, B. and Casaburi, R. (1988): Metabolic acidosis during exercise in patients with chronic obstructive pulmonary disease. *Chest,* 94: 1143-1150.
17. Tanaka, K., Matsura, Y. (1984): Marathon performance, anaerobic threshold and onset of blood lactate accumulation. *J. Appl. Physiol.,* 57: 640-643.
18. Tomlin, D.L. and Wenger, H.A. (2001): The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *J. Sports Med*., 31(1): 01-11.
19. Wasserman, K., Whipp, B. J., Casaburi, R., Beaver, W. L. and Brown, H. V. (1977): CO_2 flow to the lungs and ventilatory control. In: Muscular exercise and the lungs. Editors: Dempsey, J. A. and Reed, C. E. Madison: University of Wisconsin Press: 105 - 135.
20. Whipp, B. J. (1981): *The control of exercise hyperpnoea.* In: The regulation of breathing. Ed: Hornbein, T. New York. 1069 - 1139.
21. Whipp, B. J. and Mahler, M. (1980): *Dynamics of pulmonary gas exchange during exercise.* In: Pulmonary gas exchange. Vol. II. Ed: West, J. B. New York, Academic Press, Inc. 33 - 96.
22. Whipp, B. J. and Ward, S. A. (1990): Physiological determinants of pulmonary gas exchange kinetics during exercise. *Med. Sci. Sports Exerc.,* 22. (1): 62 - 71.
23. Whipp, B. J., Ward, S. A., Lamarra, N., Davis, J. A. and Wasserman, K. (1982): Parameters of ventilatory and gas exchange dynamics during exercise. *J. Appl. Physiol.,* 52: 1506 - 1513.