Breath-by-breath Gas Exchange Kinetics during Constant-load Work

Shunsaku KOGA

*Department of Physical Education and Ergonomics, Kobe Design University,
Gakuennishi-machi, Nishi-ku, Kobe 673, Japan*

In order to study respiratory transients during exercise, we examined breath-by-breath gas exchange kinetics during constant-load work. Five male subjects performed cycle ergometer tests which 6 min of constant-load work (150, 200, 250W) followed 50W base-line work. $\dot{V}_{CO_2}$ and $\dot{V}_{O_2}$ measured at the mouth ($(\dot{V}_{CO_2})_E$, $(\dot{V}_{O_2})_E$) and estimated at the alveolar level ($(\dot{V}_{CO_2})_A$, $(\dot{V}_{O_2})_A$) were computed breath-by-breath. The kinetic parameter (time constant) of first- and second-order exponential model was estimated using non-linear least-squares method. Our results demonstrated that a relative stability of $P_{ET_{O_2}}$, $P_{ET_{CO_2}}$, and R at their control values in the first phase. Independent of work intensities, breath-by-breath variation in gas exchange measured at the mouth was larger than those in gas exchange estimated at the alveolar level both at a non-steady state and a steady state. The time constants of $(\dot{V}_{O_2})_A$ and $(\dot{V}_{O_2})_E$ were varied with increase of work load intensity.

Key words: Respiratory transients, Alveolar gas exchange kinetics, Non-steady state

The factors contributing to the steady state responses to exercise have been investigated with work devoted to determine the response characteristics to particular dynamic work-rate forcing. Recently, there is considerable interest in modeling the kinetics of non-steady state gas exchange during exercise. In order to study respiratory transients during exercise, we examined breath-by-breath gas exchange kinetics during constant-load work.

METHOD

Five male subjects each performed cycle ergometer tests which 6 min of constant-load work (150, 200, 250 W) followed 50 W base-line work. $\dot{V}_{CO_2}$ and $\dot{V}_{O_2}$ measured at the mouth ($(\dot{V}_{CO_2})_E$, $(\dot{V}_{O_2})_E$) and estimated at the alveolar level ($(\dot{V}_{CO_2})_A$, $(\dot{V}_{O_2})_A$) were computed breath-by-breath (Beaver et al., 1981). The gas exchange measured at the mouth was obtained by measuring expired gases only (expiratory flow method). The correction for breath-by-breath changes in lung gas stores was applied to the total gas exchange which was obtained by subtract-

ing expired from inspired gas volume (alveolar gas exchange method). The individual responses were interpolated to 1-sec intervals. Aberrant values which exceeded three standard deviations from the mean were deleted from the data analysis (Lamarra et al., 1987). The 1-sec responses were further averaged across all five subjects (group mean response) in order to extract the kinetic parameters of gas exchange variables. The kinetic parameter (time constant) of a first-order single exponential model was estimated using nonlinear least-squares method. The region used for the estimation was extended to the second phase transients, excluding the initial cardio-dynamic phase from data fitting (Lamarra et al., 1987; Whipp et al., 1982). At 250 W load work, we sought to determine whether a slower exponential component was presented by fitting each data set to a model which was the sum of two exponential components. The bi-exponential function was fitted to the data at the second and the third phase, starting after the initial phase and continuing until the termination of the work load.

RESULTS

Following the onset of constant load work, P_{ETCO_2} , P_{ETO_2} , and R were maintained stable at their prior control values for the first 20 seconds (Fig.1). How-

Fig. 1 Averaged breath-by-breath response of P_{ETCO_2} , P_{ETO_2} , and R to 150W work. (From Koga, S. & H. Ikegami, 1988: Factors affecting parameter estimation of exercise gas exchange kinetics. Proceedings of the third symposium on biological and physiological engineering, Osaka: 35-38.)

Table 1. Parameterization of best-fit first-order or second-order functions for group mean responses of gas exchange variables to onset of work. (From Koga, S. et al. 1989: Breath-by-breath differences between exercise gas exchange kinetics measured at the mouth and those estimated at the alveolar level. Jpn. J. Phys. Fitness Sports Med., 38: 151-164.)

	τ_1 (sec)	r_1	τ_2 (sec)	r_2
$(\dot{V}_{O_2})_E$				
150W	43.1	0.772		
200	38.5	0.736		
250	45.4	0.856	2180	0.909
$(\dot{V}_{O_2})_A$				
150W	32.1	0.871		
200	22.5	0.927		
250	32.1	0.901	317	0.945
$(\dot{V}_{CO_2})_E$				
150W	55.5	0.868		
200	50.4	0.807		
250	55.3	0.959		0.956
$(\dot{V}_{CO_2})_A$				
150W	61.3	0.942		
200	66.9	0.981		
250	56.7	0.982		0.980

ever, on occasion, irregular breathing was shown in the first phase with P_{ETO_2} and R increasing and P_{ETCO_2} decreasing. Table 1 shows best-fit first-or second-order model values for the group mean responses of gas exchange variables to the onset of the work. At 150 W and 200 W load work, the regression coefficient (r_1) between the first-order model curve and $(\dot{V}_{CO_2})_A$, $(\dot{V}_{O_2})_A$ were higher than those of $(\dot{V}_{CO_2})_E$, $(\dot{V}_{O_2})_E$, since the breath-by-breath variation in gas

Table 2. Standard deviation of breath-by-breath fluctuations in phase 3 gas exchange variables expressed in ml/min. Individual values in 5 subjects are given together with values from group mean responses (GMR). (From Koga, S. et al. 1989: Breath-by-breath differences between exercise gas exchange kinetics measured at the mouth and those estimated at the alveolar level. Jpn. J. Phys. Fitness Sports Med., 38: 151-164.)

Subj.	Work Load W	$(\dot{V}_{O_2})_E$	$(\dot{V}_{O_2})_A$	$(\dot{V}_{CO_2})_E$	$(\dot{V}_{CO_2})_A$
1	50	150	88	118	56
	150	292	125	300	168
	200	307	132	220	188
	250	551	423	510	503
2	50	213	158	233	175
	150	234	177	203	156
	200	296	134	298	161
	250	137	123	179	104
3	50	259	148	224	90
	150	248	172	271	130
	200	414	121	402	194
	250	439	218	470	169
4	50	101	86	82	59
	150	137	101	157	105
	200	253	115	238	127
	250	198	166	189	169
5	50	261	109	174	100
	150	212	112	184	142
	200	253	106	245	101
	250	495	86	555	123
G.M.R.*	50	97	80	79	64
	150	106	62	101	80
	200	147	63	139	79
	250	109	94	122	53

*G.M.R. Group Mean Response

exchange measured at the mouth was larger than gas exchange estimated at the alveolar level during non-steady state. Table 2 shows that steady state breath-by-breath variation at the mouth level indicated by the standard deviations is larger than those at the alveolar level. $\dot{V}_{O_2}$ kinetics at the alveolar level were faster than those at the mouth, while the converse held for $\dot{V}_{CO_2}$ at the onset of constant-load work, due to the effects of fluctuations in lung gas stores on the kinetics of gas exchange at the mouth. Steady state response of $\dot{V}_{O_2}$ was not achieved and a continuous slow increase in $\dot{V}_{O_2}$ (drift) was observed in the third phase during 250 W load work. Therefore, $\dot{V}_{O_2}$ kinetics at heavy work were well characterized by the addition of a slower exponential component (time constant τ_2) to the faster component (time constant τ_1). In contrast, $\dot{V}_{CO_2}$ kinetics showed no consistent change with work rate and were not characterized by a superimposed slower component. At this work load, the breath-by-breath variation in gas exchange measured at the mouth level was larger than those at the alveolar level.

DISCUSSION

Our results demonstrated that a relative stability of P_{ETO_2} , P_{ETCO_2} , and R at their control values in the first phase and agreed with the results in previous studies (Linnarsson, 1974; Whipp et al., 1982). As suggested by Whipp et al (1982), gas exchange responses in this phase were directly proportional to the altered pulmonary blood flow. However, on occasion, inflection point between the first phase and the second phase was not distinguishable, because irregular breathing affected breath-by-breath gas exchange kinetics (Lamarra et al., 1987; Whipp et al., 1982).

Independent of work intensities, breath-by-breath variation in gas exchange measured at the mouth was larger than those in gas exchange estimated at the alveolar level both at a non-steady state and a steady state, since the variation was caused by the

invalidity of assuming zero N_2 exchange at the mouth, which was attributed to changes in lung volume (Beaver et al., 1981; Swanson & Sherrill, 1983; Wessel et al., 1979). Steady state gas exchange values at the alveolar level were equal to those obtained at the mouth level during constant load work, since the lung gas stores corrections added up to small fractions of the total gas exchange when summed over the long term (Beaver et al., 1981).

The time constants of both $(\dot{V}_{O_2})_A$ and $(\dot{V}_{O_2})_E$ were varied with increase of work load intensity. It is still a matter for debate among physiologists whether $\dot{V}_{O_2}$ kinetic system are linear or not (Di Prampero et al., 1989; Hughson et al., 1988). Recently, it is pointed out that time constant of $\dot{V}_{O_2}$ kinetic system differ between different changes in work rate (Hughson et al., 1988) and that $\dot{V}_{O_2}$ kinetics are altered in the transition from the different level of prior exercise (Di Prampero et al., 1989). Therefore, non-linearity of $\dot{V}_{O_2}$ kinetic system during exercise is suggested.

$\dot{V}_{O_2}$ drift occurring at the third phase during 250 W load work seems to reflect a delay in aerobic metabolism to cover the energy need of the working muscles. In the present study, heart rate in the third phase showed a slow continuous rise. Based on previous study which reported that the kinetics of heart rate were similar to that of cardiac output (Miyamoto et al., 1982), it is assumed that the circulatory O_2 transport in heavy exercise gradually meet the O_2 need of the working muscles. On the other hand, Casaburi et al. (1987) reported that $\dot{V}_{O_2}$ drift during heavy exercise seemed linked to lactate, though a component dictated by the work of breathing could not be ruled out.

Although estimation of working muscle O_2 consumption has been made in a few studies (Barstow & Mole, 1987; Inman et al., 1987), further studies are required for a comparison between alveolar gas exchange kinetics and tissue gas exchange kinetics.

REFERENCES

Barstow, T.J., and Mole, P.A. 1987: Simulation of

- pulmonary O_2 uptake during exercise transients in humans. *J. Appl. Physiol.*, 63(6):2253-2261.
- Beaver, W.L., Lamarra, N. and Wasserman, K. 1981: Breath-by-breath measurement of true alveolar gas exchange. *J. Appl. Physiol.:Respirat. Environ. Exercise Physiol.*, 51(6):1662-1675.
- Casaburi, R., Storer, T.W., Ben-Dov, I. and Wasserman, K. 1987:Effect of endurance training on possible determinants of $\dot{V}_{O_2}$ during heavy exercise. *J. Appl. Physiol.*, 62(1):199-207.
- Di Prampero, P.E., Mahlar, P.B., Giezendanner, D. and Cerretelli, P. 1989:Effects of priming exercise on $\dot{V}_{O_2}$ kinetics and O_2 deficit at the onset of stepping and cycling. *J. Appl. Physiol.:Respirat. Environ. Exercise Physiol.*, 66(5):2023-2031.
- Hughson, R.L., Sherrill, D.L., and Swanson, G.D. 1988:Kinetics of $\dot{V}_{O_2}$ with impulse and step exercise in humans. *J. Appl. Physiol.*, 64(1):451-459.
- Inman, M.D., Hughson, R.L., Weisiger, K.H., and Swanson, G.D. 1987:Estimate of mean tissue O_2 consumption at onset of exercise in males. *J. Appl. Physiol.*, 63(4):1578-1585.
- Lamarra, N. and Whipp, B.J., Ward, S.A., Wasserman, K. 1987:Effect of interbreath fluctuations on characterizing exercise gas exchange kinetics. *J. Appl. Physiol.*, 62(5):2003-2012.
- Linnarsson, D. 1974: Dynamics of pulmonary gas exchange and heart rate changes at start and end of exercise. *Acta Physiol. Scand. Suppl.*, 415:1-68.
- Miyamoto, Y., Hiura, T., Tamura, T., Nakamura, T., Higuchi, J. and Mikami, T. 1982:Dynamics of cardiac, respiratory, and metabolic function in men in response to step work load. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.*, 52(5):1198-1208.
- Swanson, G.D. and Sherrill, D.L. 1983:A model evaluation of estimates of breath-to-breath alveolar gas exchange. *J. Appl. Physiol.:Respirat. Environ. Exercise Physiol.*, 55(6):1936-1941.
- Wessel, H.U., Stout, R.L., Bastanier, C.K. and Paul, M.H. 1979:Breath-by-breath variation of FRC: effect on $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ measured at the mouth. *J. Appl. Physiol.:Respirat. Environ. Exercise Physiol.*, 46(6):1122-1126.
- 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.:Respirat. Environ. Exercise Physiol.*, 52(6):1506-1513.

(Received March 1, 1990)