Respiratory Response to Sinusoidal Work Load in Humans

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Present study was undertaken to elucidate possible distortion of phase response and amplitude response of various respiratory parameter such as $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ to sinusoidal work load by comparing model analysis with manual analysis. Also, an attempt was made to determine whether there is any relationship between the characteristics of response of these parameters and the aerobic capacity of subjects. Six healthy male subjects were performed exercise on an electrically braked bicycle ergometer for 32 min. The work load was varied sinusoidally between 30 watts and 60% $\dot{V}O_{2max}$ being under anaerobic threshold with periods from 1 to 16 min. These parameters were determined in breath-by-breath mode with a computer system and mass spectrometer. In model analysis, amplitude and phase responses were well described by first order exponential model, and strong correlations were observed between magnitude of phase response or time constant of amplitude response and aerobic capacity. Manual analysis revealed that respiratory responses to sinusoidal work load are not completely sinusoidal but somewhat distorted forming saw-tooth waves with steeper down-slopes.

Key words: Sinusoidal work load, Respiratory response, Gas exchange and Aerobic capacity.

Sinusoidal work loading may provide more merits for evaluation of the physiological characteristics of cardio-respiratory response to physical exercise than methods of other work loadings such as ramp, step and random work loading. Sinusoidal work loading is convenient for evaluation of the adaptability or inertiality in respiratory and circulatory functions during physical exercise. For example, the elimination of noise by superimposing response data to repeated sinusoidal works may lead to clarification of the features of the response. It is also possible to investigate the characteristics of human functions through mathematical analysis using transfer functions for response to sinusoidal work.

In many published studies, the dynamic characteristics of ventilatory and gas exchange with sinusoidal work loads are analyzed by fitting sine wave models with transfer functions (Bakker et al., 1980; Casaburi et al., 1977; Miyamoto et al., 1983;

Versteeg et al., 1981; Wigertz et al., 1970). However, this approach may eliminate some important physiological characteristics of human functions from real features, since in many cases, the response of gas exchange parameters to sinusoidal work load has been noted not to be symmetrical to the sine wave but asymmetrical to it. That is, the down-slope of response is steeper than the up-slope and vice versa. This distortion in response may be a characteristic of an individual subject and loading conditions.

The present study was undertaken to elucidate the distortion of phase response and amplitude response of various respiratory parameters such as $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ to sinusoidal work load by comparing the results of model analysis with those of manual analysis. Also, an attempt was made to determine whether there is a relationship between the characteristics of response of these parameters

and the aerobic capacity ($\dot{V}O_{2\max}$, $AT\dot{V}O_2$) of the subjects.

MEHTODS

Six healthy male subjects, aged 21~28 years, were studied. Their physical characteristics, $\dot{V}O_2$

max and $\dot{V}O_2$ at their aerobic threshold ($AT\dot{V}O_2$) are given in Table-1.

Each subject performed exercise on an electrically braked bicycle ergometer (Tsuyama Metal Co.) at a constant pedalling rate of 60 rpm. The work load was varied sinusoidally between 30 watts

Table 1. The physical characteristics, $\dot{V}O_{2\max}$ and $AT\dot{V}O_2$ of the subjects.

subj.	weight (kg)	height (cm)	age (yrs)	$\dot{V}O_{2\max}$ (ml/min)	$\dot{V}O_{2\max}$ (ml/kg·min)	$AT\dot{V}O_2$ (ml/min)	%AT (%)
N.F.	63.1	168.8	21	3609	59.1	2556	70.8
M.M.	66.7	173.0	22	3665	54.8	2295	62.6
F.Y.	70.3	170.1	21	4167	59.2	2514	60.3
M.E.	68.4	165.0	24	3614	52.2	2360	65.3
M.S.	61.2	166.0	28	3160	51.8	2330	73.7
Y.F.	64.8	168.8	24	2861	48.0	1882	65.8
Mean	65.8	168.5	23.3	3512	54.2	2323	66.4
SD	±3.09	±2.63	±2.43	±412	±4.03	±218.9	±4.58

Fig. 1 Example of $\dot{V}O_2$ response to sinusoidal work load with period of 16 minutes. Solid line : work intensity, sagit line : $\dot{V}O_2$ response, $\Delta T_0 \sim \Delta T_{270}$: time differences between work load at 0° , 90° , 180° and 270° and $\dot{V}O_2$ response at the midpoint of upslope or downslope, at the crest and at the trough.

and 60% $\dot{V}O_{2\max}$. The lowest load (30 watts) corresponded approximately to 10% $\dot{V}O_{2\max}$ of the subjects on the average, the highest load (60% $\dot{V}O_{2\max}$) being under AT for all the subjects. Warming up phase for 4 minutes with intensity of midpoint of between the both extremes preceded the sinusoidal work load. The periods of the sinusoidal work were 1, 2, 4, 8 and 16 minutes and each sinusoidal work load was continued for 32 minutes on a separate day.

Gas exchange parameters such as $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ were determined by a breath-by-breath measuring device with a computer system (Minato RM-300) and mass spectrometer (Perkin Elmer MGA-1100). The data obtained were transmitted to a personal computer (NEC Co. PC-9801) to interpolate second-by-second data, and 5 adjacent second-by-second data were averaged.

In model analysis, sine model ($Y = A_m \cdot \sin(\omega t - \theta) + b$) with amplitude (A_m) and phase shift (θ) were selected for best fitting with minimal summed-

square error using simplex's method. The phase shift was converted to seconds. Various mathematical models were used to determine the relationship between period (T) of sinusoidal work load and amplitude of response (amplitude responses of $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$), and the relationship between period (T) of the sinusoidal work load and phase shift (phase responses of $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$) to obtain the best fit. For this purpose, ① the first order exponential model, ② the second order exponential model and ③ the complex model with a first order exponential function and a linear equation were compared.

In manual analysis, interpolated second-by-second data and sine-wave of the load were plotted on the display and time differences between the load and response were measured: ① at the midpoint of upslope, ② at the crest, ③ at the midpoint of downslope and ④ at the trough. The time differences at these points were designated as $\Delta T 0$, $\Delta T 90$, $\Delta T 180$ and $\Delta T 270$, respectively (Fig.1).

Fig. 2 Relationship between amplitude response of $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ and period (T) for mean data of all subjects. The relationship was well described by first order exponential model.

RESULTS and DISCUSSION

1) Model analysis

The relationship between the period (T) of sinusoidal exercise and the amplitude of responses such as $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ was well described by first order exponential models (Fig.2). Excellent fitting of the models were indicated by extremely high correlation coefficients ($r=0.996\sim0.999$) between the data and models for these three parameters. The time constants (τ) of the models showed $\dot{V}O_2$ ($\tau=121.9$ sec) to respond more quickly to rapidly changing work intensity as well as slowly changing work intensity than $\dot{V}CO_2$ ($\tau=202.5$ sec) and $\dot{V}_E$ ($\tau=258.5$ sec). The reason why the time constant in $\dot{V}_E$ is larger than that in $\dot{V}CO_2$ can be explained by the cardiodynamic theory of $\dot{V}CO_2$ - $\dot{V}_E$ linkage (Whipp, 1987).

The correlation coefficients between the time constant (τ) of the amplitude response of the parameters and aerobic capacity expressed by $\dot{V}O_{2max}$

and $ATVO_2$ are shown in Table-2. Significantly high negative correlations were observed between the time constant in $\dot{V}O_2$ and $\dot{V}O_{2max}$ and between the time constant in $\dot{V}CO_2$ and $\dot{V}O_{2max}$. Tiedt et al. (1975) reported subjects with high PWC_{170} to have shorter time constants in transfer functions for heart rate response. Powers et al. (1985) found significantly high negative correlation coefficient ($r=-0.80$, $p<0.05$) between $\dot{V}O_{2max}$ and the half time of the $\dot{V}O_2$ response. Hagberg et al. (1980) and Hichson et al. (1978) studied the effects of endurance training on aerobic capacity and reported $\dot{V}O_{2max}$

Table 2. Correlation matrix between time constant (τ) of amplitude response and $\dot{V}O_{2max}$, and $ATVO_2$

	$\dot{V}O_2$ (τ)	$\dot{V}CO_2$ (τ)	$\dot{V}_E$ (τ)
$\dot{V}O_{2max}$	-0.822*	-0.826*	-0.577
$ATVO_2$	-0.639	-0.747	-0.397

τ : time constant of first order exponential model.

*: significant at 0.05 level.

Fig. 3 Relationship between phase shifts of $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ and period (T) for mean data of all subjects. The relationship was well described by first order exponential model

to increase after training and the initial response velocity of $\dot{V}O_2$ to become more rapid than the pretraining value. The above findings on amplitude response correspond to the results of these reports. It can be said that a person whose $\dot{V}O_{2\max}$ is high can respond more quickly and properly to a rapidly

changing work load.

The relationship between the period (T) of the sinusoidal exercise and phase response, that is, the time delay of response, to exercise was also well described by first order exponential models (Fig.3). The fitting of these models was indicated by very

Fig. 4 Complex models comprising a first order exponential function and a linear equation (left panels). Second order exponential models (right panels).

high correlation coefficients ($r=0.986\sim0.996$) and the small size of summed-square error. The magnitude (A) of phase response to the slowest sinusoidal exercise was 42.2 sec for $\dot{V}O_2$, 54.7 sec for $\dot{V}CO_2$ and 69.2 sec for $\dot{V}_E$. This order was identical to that in amplitude response mentioned already.

The reason why the time delay in $\dot{V}O_2$ response was shorter than that in $\dot{V}CO_2$ response could be explained by the larger solubility of CO_2 in the body fluid and tissue than that of O_2 . The complex

Table 3. Correlation matrix between magnitude (A) of phase response in three respiratory parameters and $\dot{V}O_{2\max}$, and $AT\dot{V}O_2$

	$\dot{V}O_2$ (A)	$\dot{V}CO_2$ (A)	$\dot{V}_E$ (A)
$\dot{V}O_{2\max}$	-0.644	-0.860*	-0.797
$AT\dot{V}O_2$	-0.847*	-0.977**	-0.846*

A: magnitude of first order exponential model.

*: significant at 0.05 level.

**: significant at 0.01 level.

models which comprising a first order exponential function and a linear equation described better the relationship between the phase response of the parameters and the period of sinusoidal work load than single first order exponential models (Fig.4). This may support Karpman's threshold theory which assumes the existence of a threshold that is the minimal intensity of exercise required to change a physiological response.

The correlation coefficients between the magnitude (A) of the phase response to the slowest sinusoidal exercise and aerobic capacity are given in Table-3. Significant correlation coefficients were obtained between $AT\dot{V}O_2$ and the magnitude of all gas exchange parameters. This relationship may partially be influenced by the magnitude of O_2 debt (Karpman, 1987). This is because the recovery of gas exchange response after the peak of the sinusoidal

Fig. 5 ΔT ($\Delta T0$, $\Delta T90$, $\Delta T180$ and $\Delta T270$) of $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ were plotted against period (T) of the sinusoidally varying work rate.

Fig. 6 Relationship between upslope or downslope at midpoint of $\dot{V}O_2$ response and the period of the load (T).

work load may be more delayed by a larger O_2 debt. The relative value of the peak exercise intensity was identical for all the subjects in the present study, being $60\% \dot{V}O_{2\max}$. This appears to indicate a smaller O_2 debt in the subject with larger aerobic capacity, resulting in negative correlations between the magnitude (A) of all gas exchange parameters and $AT\dot{V}O_2$.

2) Manual analysis

Time delay (ΔT) in the response curves of the three parameters were longest at the crest of the curve (ΔT_{90}) and shortest at the midpoint of the downslope (ΔT_{180}) during sinusoidal work load for the period of 4~16 minutes, while ΔT_{90} and ΔT_{180} appeared essentially the same during work with a shorter period (Fig.5). Thus, the slopes of respiratory responses to sinusoidal work load are not completely sinusoidal but some-what distorted saw-tooth waves with steeper downslopes. However, the response curve was virtually sinusoidal when the period of sinusoidal work load was shorter (2 minutes or less). This is evident from Fig.6. Care should be taken not to neglect this distortion in a real response when using sinusoidal mathematical models as most researchers do. The reason for this is that distortion is a physiological phenomenon which may give indication of physiological characteristics of a subject. Time difference between sinusoidal work load and response was greater at the crest than at the trough in all parameters. This may be due to larger O_2 debt at the crest and difference in the inertiality of respiratory response at the crest and trough. In the present study, O_2 debt may have been small even at the crest as well as the trough, since maximal exercise intensity, $60\% \dot{V}O_{2\max}$, was limited to less than the anaerobic threshold for each subject. Thus, the greater time difference observed at the crest may have been due to the larger inertiality at the crest.

Fig.6 shows the relationship between the period of sinusoidal work load and work slope and between this period and the upslope or downslope of

response. The slope of work load increase in inverse proportion to the period throughout the range of the latter. The slope of $\dot{V}O_2$ response was also essentially in proportion to the slope of work load between 4 and 16 minutes. However, the slope of $\dot{V}O_2$ response became flat, reaching to a plateau between 1~2 minutes. Basically the same was noted $\dot{V}CO_2$ and $\dot{V}_E$. Thus possibly, there is an upper limit to the slope of respiratory response.

Statistically significant correlation coefficients were found between ΔT_0 in $\dot{V}O_2$ and $\dot{V}O_{2\max}$ ($r = -0.826$) and between ΔT_{90} in $\dot{V}_E$ and $\dot{V}O_{2\max}$ ($r = -0.876$) suggesting negative relationships between time delays in respiratory response and aerobic capacity.

SUMMARY

Using a sinusoidal work load, the phase and amplitude response of respiratory parameters including $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ was assessed by comparing the results of model and manual analyses. The relationship between these parameters and aerobic capacity ($\dot{V}O_{2\max}$ and $AT\dot{V}O_2$) was also determined. The results and the conclusions obtained are as follows :

(1) The relationship between the period of sinusoidal exercise and amplitude response of $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ was well described by first exponential model. However, that between the period of exercise and phase shifts was better described by complex models comprising a first order exponential function and linear equation. This can be explained by Karpman's threshold theory.

(2) High negative correlations were observed between the magnitude (A) of phase response or time constant of amplitude response and $\dot{V}O_{2\max}$ and $AT\dot{V}O_2$. Significantly negative correlations were found between the magnitude in all gas exchange parameters and $AT\dot{V}O_2$. Thus, the response of respiration and gas exchange may be more rapid in man having greater aerobic capacity.

(3) Respiratory response to sinusoidal work load

with lower frequency (period (T) : 4~16 min) was somewhat distorted from an exact sinusoidal curve, indicating steeper downslope. However, the distortion was negligible for a shorter period. Larger inertiality of respiratory response at the crest of a load may be a factor responsible for this distortion.

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