Role of lower intensity part of exercise on linearity between oxygen uptake and work rate during incremental exercise in ramp function

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ORIGINAL

Role of lower intensity part of exercise on linearity between oxygen uptake and work rate during incremental exercise in ramp function.

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Abstract

The oxygen uptake ($\dot{V}O_2$) response to ramp-fashion loading of cycle ergometer shows linearity to work rate (WR), although additional $\dot{V}O_2$ is observed during high-intensity exercise of step protocol. This additional $\dot{V}O_2$ is reportedly reduced by prior exercise. We tested the hypothesis that the existence of the initial half of ramp exercise, which is assumed as prior exercise, affects the $\dot{V}O_2$ in the high-intensity part of ramp exercise to bring the linearity. Seven males (24+3 yrs, 174+5 cm, 66+5 kg) performed two bouts of incremental ramp exercise (1W increase every 6-second). In the control trial, the exercise started from 0 W, while in the experimental trial, it started from the work rate (range: 112-200 W) corresponding to the individual ventilatory threshold (Tvent). Breath-by-breath $\dot{V}O_2$ was measured in two repetitions for each trial. The $\dot{V}O_2$-WR relationship was calculated from the data above Tvent, using the same work rate range in each subject. A regression analysis revealed that the slope of $\dot{V}O_2$ to a given WR was significantly steeper in the experimental trial than in the control trial ($\dot{V}O_2$ (ml/min) =10.7 WR (W) + 382 in control; $\dot{V}O_2$ = 11.9 WR +244 in experimental; $p<0.05$). Result implies that the warm-up-like effect of the initial ramp half reduces the slow component of $\dot{V}O_2$, consequently responsible for the linear increase in $\dot{V}O_2$ during incremental ramp exercise.

Key Words: work efficiency, warm-up, slow component, incremental exercise

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Introduction

A ramp exercise test has been widely used to determine variables of physiological functions during exercise (1,2). Several texts have stated that a linear relationship exists between oxygen uptake ($\dot{V}O_2$) and work rate (WR) (3,4). Many studies have used the ramp protocol and their authors seem to be in tacit agreement with this linear relationship.

There is, however, an understanding that step function protocol at severe work load yields a slow rise in $\dot{V}O_2$ (2,5,6,7). This slow rise reflects delayed additional $\dot{V}O_2$ in working muscle during heavy exercise (8). If this slow rise in $\dot{V}O_2$ appears in ramp protocol, steeper slope should be expected in heavy to severe (upper half of the ramp) than in low to moderate intensity (initial half). The linear relationship between $\dot{V}O_2$ and WR is in conflict with this $\dot{V}O_2$ slow rise phenomenon. In fact, a few studies have reported differences in the $\dot{V}O_2$-WR relationship between lower and higher work rates during incremental exercise (9, 10,11). Zoladz et al.(11) indicated an additional

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increase in $\dot{V}O_2$ above that expected from the extrapolation of linear $\dot{V}O_2$-WR relationship. The slope of the ramp has been also reported to affect the $\dot{V}O_2$-WR relationship (10,12,13). However, additional $\dot{V}O_2$ during ramp protocol is obviously smaller than that in step protocol. As yet, factors responsible for the linearity in $\dot{V}O_2$-WR have not been elucidated.

Prior heavy exercise reportedly alters the time course of $\dot{V}O_2$ during constant heavy exercise, reducing slow component of $\dot{V}O_2$ (14,15,16). The prior heavy exercise is apparently different from the lower intensity part of ramp protocol. Nevertheless, it is possible that prior moderate intensity exercise induces the same effect on $\dot{V}O_2$ in some condition as does prior heavy exercise. If the non-linearity of $\dot{V}O_2$-WR during ramp protocol is consistent with the slow rise in $\dot{V}O_2$ during step exercise, prior exercise might decrease $\dot{V}O_2$ at a higher work rate during ramp protocol (Fig. 1). If so, the lower work rate induces the same effect as does the prior heavy exercise and consequently decreases slope of the $\dot{V}O_2$-WR relationship during a higher work rate in ramp exercise. Instead of a fortuitous balance providing the linear relationship (9), we hypothesized that the existence of a lower half of ramp protocol maintains the linearity in $\dot{V}O_2$-WR and negates the slow rise in $\dot{V}O_2$ during higher intensity. To test the hypothesis, we investigated the effect of the lower half of ramp exercise on the $\dot{V}O_2$-WR relationship. A gentle slope of ramp exercise was selected to focus on the slow rise in $\dot{V}O_2$ and to obtain many data points, because steep slope ramp may limit the amount of data available for analysis (9).

Methods

Seven healthy males (Table 1) volunteered for this study after giving informed consent to the procedure. All subjects had participated our other experiments and accustomed to the experimental environment.

All subjects performed an incremental test on an electrical braked cycle ergometer (Model 232C, Combi, Japan) to determine their maximal oxygen uptake and ventilatory threshold (Tvent). This ergometer was checked and calibrated within two month of the present experiment. he subject started cycle at 20 W and the power output was increased by 1 W every 3 s (20W/min). The pedaling frequency was maintained at 60 rmp with auditory signals. The subjects continued exercise until he could not maintain a pedaling frequency of more than 50 rpm. Respiratory flow through a mask was measured with a hot wire flow meter (RM300, Minato Medical Sciences, Japan). Respired O_2 and CO_2 concentrations were analyzed with a mass spectrometer (WSMR1400, Westron, Japan).
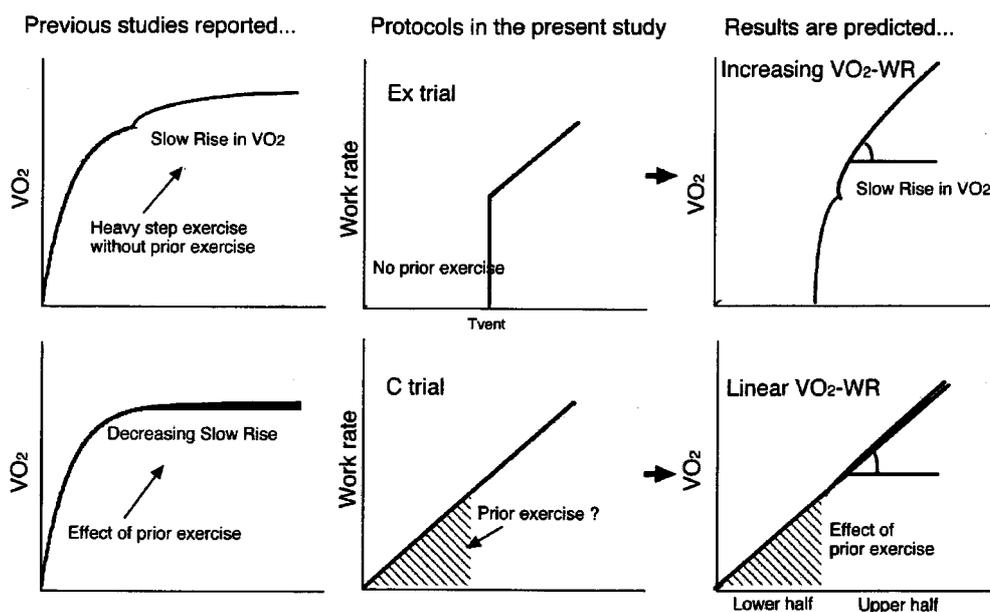

Figure 1.Scheme of the VO_2-WR relationship deduced from the present and previous studies. Previous studies reported that prior exercise alters the VO_2 slow component (left). We speculated that ramp exercise without a lower half (upper middle) would induce a slow rise in VO_2 (upper right), while normal ramp exercise (lower middle) would maintain the linearity of the VO_2-WR relationship (lower right), because of the effect of prior exercise, i.e., the lower half of the ramp protocol.

Breath-by-breath gas exchange variables were calculated by RM300. This system was calibrated by using a 2 L syringe with fresh outdoor air and precision gas (O_2 15%, CO_2 5%) before each test and was checked after each test. No systemic difference between before and after each test was detected. The heart rate was calculated from the interval of a transistor-transistor logic signal synchronized with the R wave from an electrocardiogram (OEC8201, Nihon-Koden, Japan). Tvent was established as the $\dot{V}O_2$ at which cardon dioxide output ($\dot{V}CO_2$) and minute ventilation ($\dot{V}_E$) started to rise without a simultaneous rise in the $\dot{V}_E/\dot{V}CO_2$ ratio.

Each subject then performed two incremental ramp exercises on different days. In the control slow ramp protocol (C trial), the initial work rate was 0 W and the power output was increased by 1 W every 6 S (10 W/min). In the slow ramp trial without below-Tvent exercise (Ex trial), exercise started from the work rate corresponding to the $\dot{V}O_2$ of the individual Tvent. Each subject repeated each trial twice on different days with interval more than two days. Subjects exercised until exhaustion in the first trial. In the second trial, subjects exercised until exhaustion or the work rate attained the peak work rate of the first trial. The measurements of gas exchange and heart rate were the same as those mentioned above. The order of the trials was randomized.

The $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and HR were linearly interpolated once a second, and averaged for two trials in each subject and trial. The relationship between WR and $\dot{V}O_2$ was calculated with a linear regression analysis. The WR range of data used for calculation was from 30W above individual Tvent (3 min after the Tvent) to 10 W lower than the peak WR (1 min before the end of exercise) for the upper ramp half. The same range was used in both trials. The relationship in the lower ramp half has from 30 W to 20 W below the individual Tvent. To determine whether there is an effect of data range selected for calculation of the slope, the data range was varied every 10 W with settling at either the lower point (30 W above the Tvent) or higher point (10 W below peak WR).

Data are presented as mean ± SD. The significance of difference was assessed using paired t-test, with significance accepted at $p < 0.05$.

Results

Figure 2 shows an example(subject no. 7) of $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and HR in the upper half as function of WR in the C and Ex trials. The $\dot{V}O_2$-WR relationship in the C trial is linear. Also the $\dot{V}O_2$-WR relationship after 3 min of starting the work load (160 W, i.e., Tvent plus 30 W) in the Ex trial is linear. The $\dot{V}CO_2$, $\dot{V}_E$ and HR are higher in the Ex trial than in the C trial above 160 W. Seemingly, the difference in $\dot{V}O_2$-WR relationship between both trials was not clear in this figure.
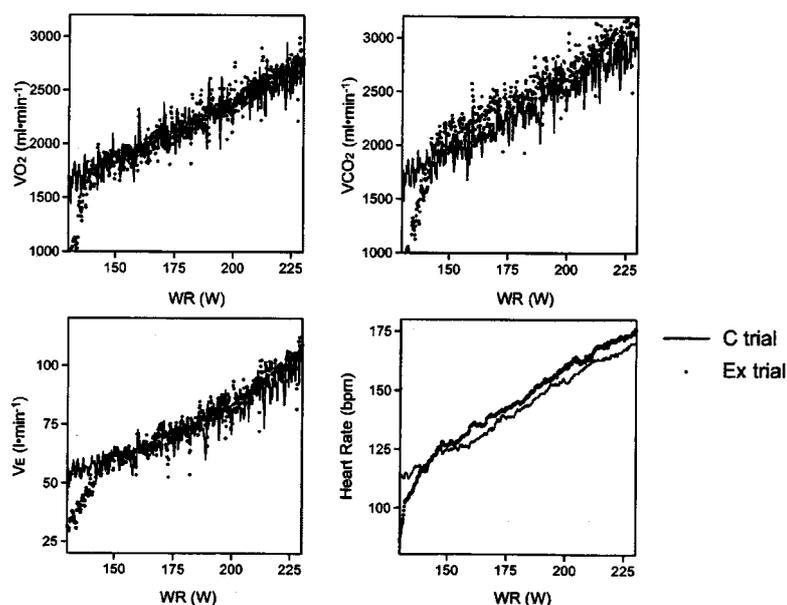

Figure 2. Responses of oxygen uptake (VO₂; upper left), carbon dioxide production (VCO₂; upper right), minute ventilation (Vₑ; lower left), and heart rate (lower right) to the trials for subject 7 are shown. The VO₂-WR slope could not seemed to be higher in the Ex trial than the C trial from 30W above the Tvent to the peak WR. However, the VO₂-WR slope in the upper half of the ramp exercise was different between the trials (see text and Table 2).

There is a significant difference in the $\dot{V}O_2$-WR relationship in the upper ramp half between the trials. The slopes of the relationship (Table 2) was significantly steeper in the Ex trial (11.86+0.42 ml/min •W) than in the C trial (10.69+0.65 ml/min •W). The intercept of the relationship showed no significant difference between the C (382+126 ml/min) and the Ex trials (244 + 182 ml/min). The $\dot{V}O_2$-WR relationship in the lower ramp half ($\dot{V}O_2$ = 10.77 WR + 364, SD 0.8 and 94, respectively) was not significantly different from the upper ramp half in the C trial.

Figure 3 shows the $\dot{V}O_2$-WR relationships of all subjects. To focus on the different slope, the $\dot{V}O_2$ is shown as mean for one minute. The Ex trial shows the steeper slope than the C trial.

We tested whether there is an effect of data range used for calculation. The $\dot{V}O_2$-WR relationship calculated from data over various spans is shown in Figure 4. The slopes are different, with some comparisons being significantly different between the trials when the shorter data span was used. The intercept was not significantly different between the trials even when using various data spans.
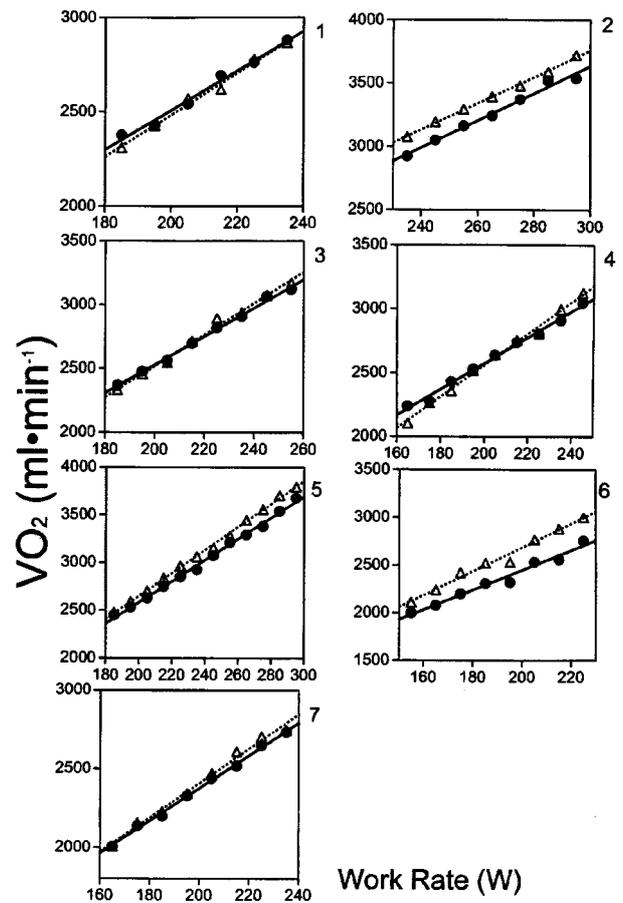

Figure 3. VO₂ and WR relationship of all subjects. The upper right number indicates subject's number. The VO₂-WR slope is steeper in the Ex trial than the C trial in all subjects. The data over the range of horizontal axis was used for calculation in the Table 2.
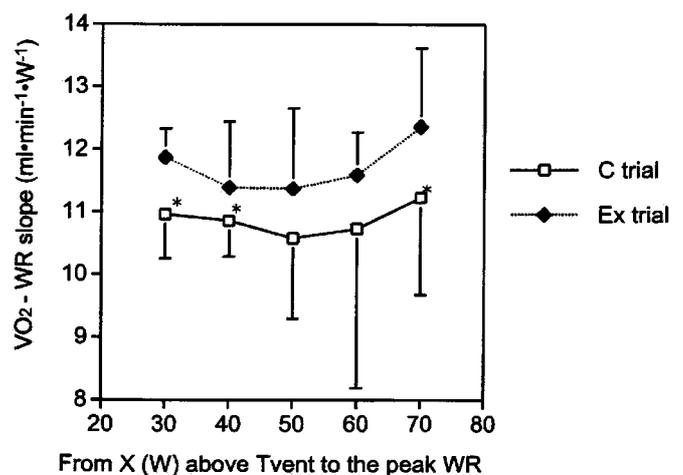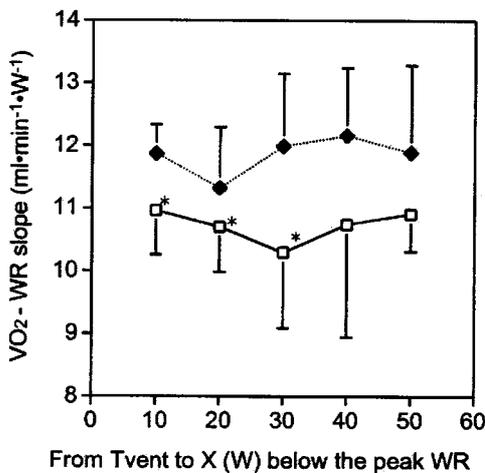

Figure 4. Effect of data range on VO₂-WR slope. The horizontal axis indicates how many watts below the peak WR (left) or above the Tvent (right) were used for the regression analysis. Asterisks indicate a significant difference from the Ex trial. Although there are some differences as to the existence of significant differences, the slope of the Ex trial was steeper over various data ranges.

Table 1. Characteristics of subjects

Subject No.	Age (yrs)	Height (cm)	Weight (kg)	VO2max (L/min)	WRmax (Watts)	Tvent (L/min)	WR @Tvent (Watts)
1	27	182	73	3.6	300	1.8	149
2	19	169	60	3.9	345	2.4	200
3	25	178	68	2.8	252	1.5	112
4	24	173	63	3.3	300	1.7	133
5	24	167	63	3.8	344	2.0	150
6	24	172	65	2.9	269	1.5	120
7	26	177	71	3.1	272	1.6	130
mean	24.1	174.0	66.1	3.34	297.4	1.79	142.0
SD	2.5	5.3	4.7	0.44	36.4	0.32	29.1

Table 2   The slope of the V̇O$_2$-WR relationship in the upper half of the ramp for both trials and the lower half of the ramp for the control tirlal.

Subject No	C trial		Ex trial		Lower half	
	slope mL/min/W	intercept mL/min	slope mL/min/W	intercept mL/min	Slope mL/min/W	intercept mL/min
1	9.80	551	10.99	287	10.60	338
2	10.96	365	11.85	594	9.80	514
3	11.81	155	12.24	63	10.38	371
4	10.67	447	12.17	119	11.72	287
5	10.85	417	12.14	219	12.05	279
6	10.05	438	11.85	323	10.12	468
7	10.51	301	11.67	103	10.70	289
mean	10.69	382.0	11.86*	244.0	10.77	363.7
SD	0.65	126.2	0.42	182.3	0.84	93.8

*:significant difference vs. C trial (p<0.05)

Discussion

The main finding in the present study was that the ramp protocol without the lower half (below Tvent) showed greater V̇O$_2$-WR slope than did the normal ramp protocol. This result implies that the lower-intensity part of ramp exercise is responsible for the linearity of the V̇O$_2$-WR relationship during ramp protocol exercise.

Previous studies reported that prior exercise altered the V̇O$_2$ response to heavy or severe exercise(14,15,16), indicating that prior exercise decreases the slow rise in V̇O$_2$ and that this effect alters the V̇O$_2$ in ramp exercise. It has not yet been established which conditions and what mechanisms alters the V̇O$_2$ during heavy to severe exercise. Gerbino et al. (14) reported that low-intensity prior exercise did not alter the V̇O$_2$ response to heavy exercise. It is, however, possible that low-intensity

exercise alters the $\dot{V}O_2$ response when there is no interval between the prior and main exercises. For example, low-intensity prior exercise induced the faster $\dot{V}O_2$ response to main low-intensity exercise (17). It is also possible that whether prior exercise alters the $\dot{V}O_2$ in the main exercise depends on the time interval between the prior and main exercises, as well as the intensity of the prior exercise. Unfortunately, the physiological background for maintaining the linearity of the $\dot{V}O_2$-WR slope remains unclear until the physiological significance of the prior exercise on $\dot{V}O_2$ slow rise is determined.

Rather than a fortuitous balance in the linear relationship of WR and $\dot{V}O_2$ as suggested in the previous report (9), we hypothesized that the first half of the ramp exercise induces a similar effect as of that prior exercise on $\dot{V}O_2$ to maintain the linear relationship. This hypothesis could be accepted, if ramp exercise without lower half ramp produces a higher $\dot{V}O_2$-WR slope, compared to normal ramp exercise. The hypothesis was partly accepted by the present result because the slope of the $\dot{V}O_2$-WR in the upper half was higher in the ramp protocol without lower half than in the normal ramp protocol. When the progressive slow rise in $\dot{V}O_2$ observed during step protocol of heavy intensity appears in ramp protocol, there should be an additional rise shown in the linear $\dot{V}O_2$-WR relationship during heavy to severe part of the ramp protocol. The present Ex trial had higher $\dot{V}O_2$-WR slope compared to that of the C trial. This corresponds to the slow rise in $\dot{V}O_2$ during step protocol. The slow rise in $\dot{V}O_2$ was seen only in the Ex trial. This result indicates that a certain effect of prior exercise decreases the $\dot{V}O_2$-WR slope. This implies that the $\dot{V}O_2$-WR linearity results from an unknown effect of prior exercise, and that this effect negates the slow rise in $\dot{V}O_2$ during ramp exercise.

Zoladz et al. (11) pointed out a discrepancy between the classical linear $\dot{V}O_2$-WR relationship (3,4) and the slow rise in $\dot{V}O_2$ during heavy to severe exercise (2,5,7,18). Assuming that pulmonary $\dot{V}O_2$ closely reflects leg $\dot{V}O_2$ (8,19), it seems acceptable that linearity exists between $\dot{V}O_2$ as an index of energy consumption and WR as index of energy output. This is, however, in conflict with the slow rise in $\dot{V}O_2$ observed during heavy to severe intensity exercise.

We propose that the linearity in the $\dot{V}O_2$ as a function of WR during ramp protocol is consisted of the balance between the slow rise in $\dot{V}O_2$ ($\dot{V}O_2$ increase) and an effect of prior exercise on slow rise in $\dot{V}O_2$ ($\dot{V}O_2$ decrease). In the C trial, the lower-intensity exercise must induce a effect of prior exercise on $\dot{V}O_2$ and keep the $\dot{V}O_2$ linear, and consequently there was no difference between the lower and upper halves in $\dot{V}O_2$-WR slope. In contrast, in the Ex trial, there was no prior exercise, thus slow rise in $\dot{V}O_2$ increasing the $\dot{V}O_2$-WR slope. These results suggest that the existence of the lower half in the incremental ramp protocol maintain the $\dot{V}O_2$-WR slope linear.

The factors inducing the slow rise in $\dot{V}O_2$ have been investigated. It was established that the exercising muscle is the predominant site (8,19). Although possible factors such as muscle temperature (20) and muscle fiber type distribution (6) have been proposed and tested, the factors have not been determined as yet. Nevertheless, it is clear that prior exercise alters the $\dot{V}O_2$ response in heavy to severe intensity exercise (14,15,16), particularly the slow rise in $\dot{V}O_2$ is decreased by prior exercise. This effect oriented the $\dot{V}O_2$-WR slope downwards, overcoming the slow rise in $\dot{V}O_2$ during ramp protocol.

We should refer to the limitation of the present interpretation of the model we used. We used linear model to simplify the calculation, and did not take the convolution of the step and ramp into account as to render the model simple. Considering the convolution of the step and ramp functions, however, the delay from ramp function could induce delay on the $\dot{V}O_2$ response. If so, the different slope might have been influenced by the delay.

It was found that there are significant differences between lower halves and upper halves of the $\dot{V}O_2$-WR slopes during 20, 30, 40 W/min ramp protocols, whereas there was no significant difference during a 10 W/min protocol. This result obtained from 10/min protocol is consistent with the present results. We can speculate a possible explanation for these results that the prior exercise duration was sufficient for evoking the effect of lower half on the $\dot{V}O_2$-WR slope of upper half. The effect of lower half ramp exercise on the

$\dot{V}O_2$-WR slope might be intensity- and time- dependent.

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