

Metabolic and Respiratory Responses During the Performance of a One-Hour Man Test 4

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Abstract

Human physiological variables, such as body weight, height, strength, and aerobic capacity, can affect the results of such exercise tests as that used for Man Test 4 (MT4), a NIOSH respirator certification test described in 42 C.F.R. Part 84 (1999). The purposes of this research were to characterize the metabolic responses of men with varying body weights performing a one-hour MT4 and to compare these results to Kamon's earlier steady-state testing results (Kamon, *et al.*, 1975). Fourteen male volunteers performed MT4 for one hour while they wore a portable, telemetric metabolic measurement device weighing 0.6 kg. The subjects were stratified into four body weight categories: 80 - 86 kg (n=4); 86.1 - 92 kg (n=4); 92.1 - 100 kg (n=4); and >100 kg (n=2). Heart rate (HR), minute ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), and respiratory quotient (RQ) were measured for every breath and averaged for each minute of each task. Mean MT4 $\dot{V}O_2$ was significantly greater for the 86 - 92 kg (1.41 L/min), 92 - 100 kg (1.53 L/min), and >100 kg (1.70 L/min) groups than for the 80 - 86 kg group (1.06 L/min, $p < 0.05$). Mean MT4 $\dot{V}CO_2$ was significantly greater for the 92 - 100 kg (1.40 L/min) and >100 kg (1.41 L/min) groups than for the 80 - 86 kg group (1.07 L/min, $p < 0.05$). Mean MT4 $\dot{V}_E$ and RQ for the >100 kg group were significantly greater than for the 80 - 86 kg group ($p < 0.05$). Mean MT4 HR for the two lowest body weight groups was significantly lower than that of the >100 kg group ($p < 0.05$). For all MT4 tasks except the Overcast and Sample periods, $\dot{V}O_2$ was lower than that reported in previous research (Kamon, *et al.*, 1975). These differences are the result of the absence of steady-state conditions in the current study.

Introduction

Under the authority of the Mine Safety and Health Act of 1969, regulatory requisites were announced for the use of Man Test 4 (MT4) as a certification test by the National Institute for Occupational Safety and Health (NIOSH) to set the duration of a closed-circuit self-contained breathing apparatus (SCBA). The one-hour MT4 is an ordered set of six different exercise tasks and four rest periods performed at different frequencies and durations over the course of 60 minutes, as described in 42 C.F.R. Part 84 (1999). These regulations describe how an SCBA must pass all performance requirements, while being worn by a test subject performing the one-hour MT4, in order to be certified as having a service time of one hour.

The MT4 activities include treadmill walking, treadmill running, laddermill climbing, pulling and releasing a pulley attached to a 20 kg weight, lifting and transporting a 23 kg load, and walking while carrying a 20 kg load. Except for pulling and releasing the pulley, the energy expenditure associated with the activity is dependent on body weight. Since the energy requirements for a given activity varies with differences in body weight, the total energy expenditure (measured as oxygen consumption) for MT4 may be different throughout a range of body weights. In addition, because MT4 activities occur sequentially with four rest periods during the course of the protocol, the metabolic requirements for one activity may influence the oxygen consumption measured for a subsequent activity.

Kamon, *et al.* (1975) reported research data on the steady-state respiratory and metabolic responses to the one-hour MT4 activities in an effort to provide information on the expected respiratory responses during an

actual MT4. That study reported minute ventilation, oxygen consumption, and carbon dioxide production requirements of coal mining and non-mining respirator users. The mean body weight of the miners was assumed to represent the 50th percentile body weight of the U.S. mining population. The durations of the activities during an actual MT4 vary to the extent that they may not be of sufficient duration to achieve a steady-state response. For example, periods of treadmill walking during the MT4 have durations of 2 to 6 minutes, and the single period of treadmill running has a duration of one minute.

The purposes of this study were to examine the effects of body weight on the respiratory and metabolic responses to MT4 and to compare these results to Kamon's earlier steady-state testing results (Kamon, *et al.*, 1975).

Methods

The subjects for this study were 14 men between the ages of 24 and 48 years. All study subjects participated in a NIOSH respirator certification panel as test subjects.

Prior to participating in the study, all subjects read and signed an informed consent as is required by the NIOSH Human Subjects Review Board. Each subject had completed a comprehensive physical exam within 12 months of the testing. Each subject was placed in one of four body weights groups: 80 - 86 kg, 86.1 - 92 kg, 92.1 - 100 kg, and >100 kg.

The metabolic and respiratory data was measured and collected on each subject with a K4 b^2 telemetered, breath-by-breath metabolic measurement system (COSMED, Srl, Rome, Italy). Validation research for the K4 system has been published elsewhere (Bishop, *et al.*, 1995). The K4 b^2 system weighed 600 grams and was calibrated before and after each test. After each subject was fitted with the nose cup, a leak check was performed. Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), heart rate (HR), minute ventilation ($\dot{V}E$), and respiratory quotient (RQ) were measured for every breath and averaged for each minute of each task. All respiratory data was reported as STPD.

While wearing the K4 b^2 system, each subject completed a one-hour MT4 protocol. Table 1 lists the order and duration of MT4 activities. These activities consisted of walking (Walk) and running (Run) on a Quinton Q55 treadmill (Bothell, WA); climbing a vertical treadmill (National Draeger, Inc., Pittsburgh, PA) at 30 centimeters (1 foot) per second (Laddermill); pulling on a 20 kilogram (45 pound) weight attached to a pulley a distance of 1.52 meters (5 feet) and controlling the release of the weight to its original position (Rope Pull); transporting a 23 kilogram (50 pound) weight up a 35° ramp for 3.05 meters (10 feet), across a 2.44 meter (8 foot) platform elevated to a height of 1.83 meters (6 feet), and back down the ramp to the starting position (Overcast); and, carrying a 20 kilogram (45 pound) weight on one shoulder while walking on a treadmill (Carry). "Sample" was a standing rest period. While walking and running, subjects were allowed to place one hand on the side rail of the treadmill.

Overall test means were analyzed for the effects of body weight using a repeated measures analysis of variance and linear regression (SAS Institute, Cary, NC). Individual task means were analyzed for body weight effects using a 1-way analysis of variance, where multiple comparisons were made using the Student-Newman-Keuls test at $\alpha=0.05$ (SigmaStat, San Rafael, CA). T-tests were used to compare Kamon's 50th percentile task mean $\dot{V}O_2$ to pooled task mean $\dot{V}O_2$ for the lowest two body weight groups of the current study.

Table 1. The order and durations of the one-hour Man Test 4 activities

1. Sample for 2 min	10. Run at 9.7 km/h for 1 min
2. Walk at 4.8 km/h for 2 min	11. Overcast (6 times) for 9 min
3. Laddermill at 30 cm/sec for 1 min	12. Rope Pull (36 times) for 3 min
4. Walk at 4.8 km/h for 2 min	13. Sample for 2 min
5. Rope Pull (60 times) for 5 min	14. Walk at 4.8 km/h for 6 min
6. Walk at 4.8 km/h for 3 min	15. Rope Pull (60 times) for 5 min
7. Overcast (4 times) for 8 min	16. 20 kg Carry at 4.8 km/h for 3 min
8. Sample for 2 min	17. Sample for 2 min
9. Walk at 4.8 km/h for 4 min	

Results

Subject characteristics by body weight group are presented in Table 2. Groups were somewhat similar for age and height. Test mean $\dot{V}O_2$, $\dot{V}CO_2$, VE, HR, and RQ results for the one-hour MT4 are presented in Table 3. Mean MT4 $\dot{V}O_2$ was significantly greater for the 86 - 92 kg, 92 - 100 kg, and >100kg groups than for the 80 - 86 kg group ($p<0.05$). Mean MT4 $\dot{V}CO_2$ was significantly greater for the 92 - 100 kg ($1.40 \text{ L} \cdot \text{min}^{-1}$) and >100 kg groups ($1.41 \text{ L} \cdot \text{min}^{-1}$) than for the 80 - 86 kg group ($1.07 \text{ L} \cdot \text{min}^{-1}$, $p<0.05$). Mean MT4 VE and RQ for the >100 kg group were significantly greater than those of the 80 - 86 kg group ($p<0.05$). Mean MT4 HR for the two lowest body weight groups were significantly lower than that of the >100 kg group ($p<0.05$).

Table 2. Group mean $\pm$ S.D. for age, body weight, and height (n = 14)

Body Weight Group	Age (yr)	Body Weight (kg)	Height (cm)
80-86 kg (n=4)	38 $\pm$ 9.1	81.7 $\pm$ 1.3	180.2 $\pm$ 2.1
86-92 kg (n=4)	45 $\pm$ 1.7	90.8 $\pm$ 0.9	171.5 $\pm$ 3.9
92-100 kg (n=4)	32 $\pm$ 7.1	96.9 $\pm$ 0.3	181.0 $\pm$ 5.7
>100 kg (n=2)	38 $\pm$ 14.1	104.0 $\pm$ 5.7	179.0 $\pm$ 1.4

Table 3. Mean $\pm$ S.D. for test mean oxygen consumption ($\dot{V}O_2$, STPD), carbon dioxide production ($\dot{V}CO_2$, STPD), minute ventilation ($\dot{V}E$, STPD), heart rate (HR), and respiratory quotient (RQ)

Body Weight Group (kg)	Test Mean $\dot{V}O_2$ (L/min)	Test Mean $\dot{V}CO_2$ (L/min)	Test Mean $\dot{V}E$ (L/min)	Test Mean RQ	Test Mean HR (beats/min)
80-86	1.06 ± 0.32	1.07 ± 0.36	27.4 ± 8.2	1.02 ± 0.09	111** ± 14.6
86-92	1.41* ± 0.37	1.25 ± 0.35	31.6 ± 8.0	0.91 ± 0.09	113** ± 13.4
92-100	1.53* ± 0.39	1.40* ± 0.39	34.5 ± 8.5	0.93 ± 0.10	122 ± 13.1
>100	1.70* ± 0.39	1.41* ± 0.38	35.1* ± 8.5	0.83* ± 0.07	144 ± 13.5

* $p < 0.05$ compared to 80-86 kg group

** $p < 0.05$ compared to >100 kg group

Significant linear relationships between $\dot{V}O_2$ and $\dot{V}CO_2$ and body weight were observed. The regression equations are as follows:

$$\dot{V}O_2 = 0.029 \times \text{body weight} - 1.29 \quad (R = 0.78, p < 0.001) \quad (1)$$

$$\text{and } \dot{V}CO_2 = 0.017 \times \text{body weight} - 0.30 \quad (R = 0.76, p < 0.002) \quad (2)$$

Tables 4 and 5 show the MT4 task mean differences in $\dot{V}O_2$ due to body weight. Values are mean $\dot{V}O_2$ for the duration of the task. Table 4 presents differences for the Walk and Sample periods. Values for the >100 kg group were significantly greater than those of the 80 - 86 kg group ($p < 0.05$) for all except the fourth Walk period. For the first Sample period, $\dot{V}O_2$ was significantly lower for the lightest three body weight groups as compared to the >100 kg group ($p < 0.05$). For the third Sample period, $\dot{V}O_2$ was significantly greater for the heaviest two body weight groups as compared to the 80 - 86 kg group ($p < 0.05$). Table 5 presents differences for the remaining tasks. For both the first Overcast period and the Laddermill, $\dot{V}O_2$ was significantly greater for the heaviest three body weight groups as compared to the 80 - 86 kg group ($p < 0.05$). For the Carry task, $\dot{V}O_2$ for the > 100 kg group was significantly greater than that of the 80 - 86 kg group ($p < 0.05$).

Table 4. Mean $\dot{V}O_2$ (L/min, STPD) for Walk and Sample periods

Task	Body Weight Group			
	80-86 kg	86-92 kg	92-100 kg	>100 kg
Walk 1	0.78	1.08*	1.31*	1.37*
Walk 2	1.49	2.01	2.12	2.53*
Walk 3	1.11	1.43	1.60*	1.81*
Walk 4	0.89	1.27	1.41	1.40
Walk 5	0.96	1.34*	1.37	1.60*
Sample 1	0.28**	0.44**	0.51**	0.81
Sample 2	0.41	0.61	0.77	0.90
Sample 3	0.67	0.99	0.99*	1.37*
Sample 4	0.59	0.94	1.05	1.32

* p<0.05 compared to 80-86 kg group

** p<0.05 compared to >100 kg group

Table 5. Mean $\dot{V}O_2$ (L/min, STPD) for Rope Pull, Overcast, Laddermill, Run, & Carry

Task	Body Weight Group			
	80-86 kg	86-92 kg	92-100 kg	>100 kg
Rope pull 1	1.25	1.47	1.69	1.79
Rope pull 2	1.20	1.62	1.62	1.90
Rope pull 3	1.30	1.63	1.66	1.93
Overcast 1	0.96	1.35*	1.49*	1.74*
Overcast 2	1.25	1.65	1.85	1.72
Laddermill	1.49	2.02*	2.14*	2.60*
Run	1.43	1.92	2.09	1.95
Carry	1.31	1.69	1.76	2.09*

* p<0.05 compared to 80-86 kg group

Tables 4 and 5 results also demonstrate the range of task means within identical tasks. For the lowest body weight group, walking at the same speed and grade required an oxygen consumption of 0.78 L/min during the first Walk period and 1.49 L/min during the second Walk period. For the highest body weight group, the $\dot{V}O_2$ for the same Walk periods ranged from 1.37 L/min to 2.53 L/min. According to the MT4 protocol (Table 1), the activity preceding the first Walk period was a Sample period and the activity preceding the second Walk period was the Laddermill task.

Discussion

The differences due to body weight in mean MT4 $\dot{V}O_2$ and $\dot{V}CO_2$ observed in the current study are practically as well as statistically significant. Using this study's Equation 1, a 56.3% difference in mean MT4 $\dot{V}O_2$ would be predicted for an 80 and 100 kg subject. Over a one-hour period, the total oxygen required by an 80 kg and 100 kg subject would be 61.8 and 96.6 Liters, respectively. These large differences in oxygen requirements could result in performance differences in respirators undergoing MT4 certification testing.

Since body weight has a significant effect on the metabolic and respiratory responses to MT4 tasks, information about the body weight characteristics of the U.S. coal mining population is relevant to this discussion. The work by Kamon and colleagues (1975) proposed that the 50th percentile of male miners using respiratory protection weighs 87 kg and estimated that the 95th percentile of users weighs 105 kg. In a large cohort study of U.S. coal miners (Wang, *et al.*, 1996), the mean ($\pm$ S.D.) body weights reported were 80.8 ($\pm$ 14.6) kg from data collected in 1969-1975 and 87.0 ($\pm$ 17.9) kg in data from 1977-1988. From a report on a large study that examined 364 U.S. underground miners between 1980 and 1984 (Ayoub, *et al.*, 1984), the mean ($\pm$ S.D.) body weight was 80.4 ($\pm$ 12.2) kg for all underground miners and 79.8 ($\pm$ 12.4) kg for coal miners. Updated demographic data for the coal mining population are needed to characterize the population accurately and to determine the level of protection which may be provided by MT4.

The second purpose of this study was to compare the results of landmark research by Kamon, *et al.* (1975) to the results from running the MT4 protocol as if testing an SCBA for NIOSH certification. Using pooled data from the 80-86 kg and 86-92 kg body weight groups and data from the >100 kg group, comparisons can be made between the previous research and the present study (Table 6).

Table 6. NIOSH task mean $\dot{V}O_2$ and Kamon's task mean $\dot{V}O_2$ (L/min, STPD)

Task	NIOSH 86 kg (pooled, n=8)	Kamon's 87 kg	NIOSH 104 kg (n=2)	Kamon's 105 kg (calculated)
Walk	1.20	1.29 (n=24)	1.67	1.69
Sample	0.61	0.35	1.10	0.35
Rope Pull	1.41	1.72 (n=33)	1.87	2.29
Overcast	1.31	1.31 (n=33)	1.73	1.66
Laddermill	1.75	3.60* (n=7)	2.60	4.52
Run	1.67	2.91* (n=15)	1.95	3.45
Carry	1.50	1.82* (n=12)	2.09	2.18

* $p < 0.002$ as compared to NIOSH 86 kg

For the Laddermill, Run, and Carry tasks, Kamon's mean $\dot{V}O_2$ for his 50th percentile group was significantly greater than that seen in the present study (Kamon, *et al.*, 1975). Research design may account for the different results seen in the two studies. For example, Kamon allowed his subjects to rest between tasks to complete recovery; the MT4 protocol allows resting to occur only during the four Sample periods, which are 2 minutes in duration. Kamon measured respiratory gases only during the last minute of each task after each subject had exercised a minimum of five minutes; the present study measured every breath of every minute.

Figure 1 illustrates the pooled minute average and mean task $\dot{V}O_2$ for the two lowest body weight groups of the current study (mean body weight of 86 kg), and Kamon's (Kamon, *et al.*, 1975) steady-state $\dot{V}O_2$ values for the 50th percentile body weight (graphed as continuous data). Figure 2 depicts the minute average $\dot{V}O_2$ data and task mean $\dot{V}O_2$ for the >100 kg body weight group from the present study and Kamon's (Kamon, *et al.*, 1975) estimated steady-state values for the 95th percentile body weight subject (graphed as continuous data). Figures 1 and 2 indicate a general dampening of $\dot{V}O_2$ when the results from an actual MT4 protocol are compared to the steady-state data of Kamon (Kamon, *et al.*, 1975).

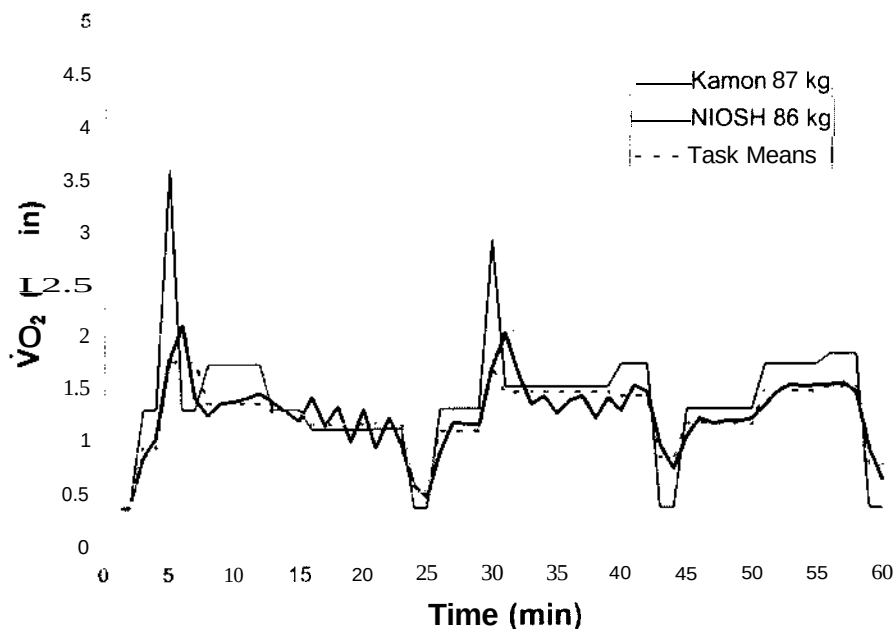


Figure 1. Minute average oxygen consumption ($\dot{V}O_2$) and task mean $\dot{V}O_2$ for pooled 80 - 86 and 86 - 92 kg groups ($n = 8$, mean body weight = 86 kg), and 50th percentile steady-state $\dot{V}O_2$ from Kamon (1975).

Peaks in $\dot{V}O_2$ are shown to be reduced further when minute data are averaged into task mean data. Since several activities in MT4 have shorter durations than the five-minute minimum duration used in the earlier research, the subjects in the current study may not have been physically active for a sufficient duration to reach steady-state levels. Bernard *et al.* (1977) described the $\dot{V}O_2$ and $\dot{V}E$ differences between the shorter measured work periods and steady-state work periods as a "physiological deficit." In addition, the subjects in the present study performed the MT4 activities in serial order, which resulted in a higher $\dot{V}O_2$ during the rest periods (Sample). Subjects in Kamon's study (Kamon, *et al.*, 1975) were allowed to rest to full recovery between tasks.

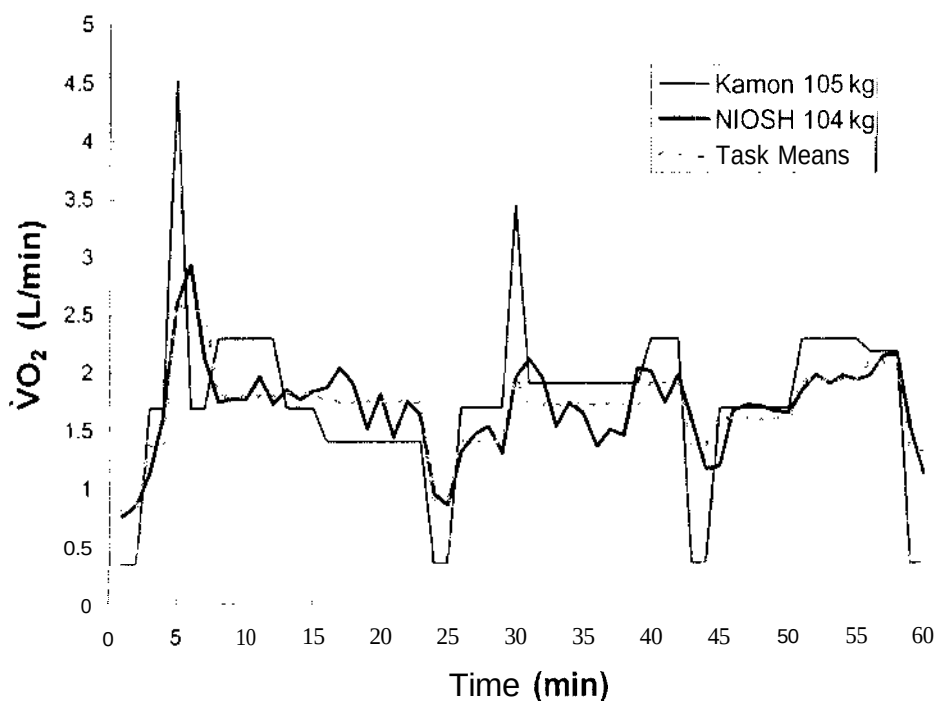


Figure 2. Minute average oxygen consumption ($\dot{V}O_2$) and task mean $\dot{V}O_2$ for > 100 kg group ($n = 2$, mean body weight = 104 kg), and 95th percentile steady-state $\dot{V}O_2$ from Kamon (1975).

If Equation 1 from the present study were used to predict test mean $\dot{V}O_2$, 1.23 L/min of oxygen would be consumed by an 87 kg man performing a one-hour MT4. The difference between the predicted $\dot{V}O_2$ from this research and the estimated test mean $\dot{V}O_2$ for an 87 kg man from Kamon's study (1.35 L/min) may be explained by Kamon's use of steady-state results instead of actual MT4 results (Kamon, *et al.*, 1975). In addition, not all of Kamon's subjects were used for all tasks; the mean bodyweights of the subsets of subjects performing each task may not have been 87 kg.

These results have implications for the development of a potential test protocol to be performed on the Automated Breathing and Metabolic Simulator (ABMS) as a supplemental certification test. The ABMS is a computer-controlled system designed to simulate human $\dot{V}O_2$, $\dot{V}CO_2$, and $\dot{V}E$ (Kyriazi, 1986). The present study provides minute-by-minute MT4 data which may be appropriate for use in the development of a simulated MT4 ABMS test protocol.

Summary and Conclusions

In summary, significant effects of body weight on MT4 mean $\dot{V}O_2$ and $\dot{V}CO_2$ were observed in the present study. Mean MT4 $\dot{V}O_2$ was significantly greater for the 86 - 92 kg, 92 - 100 kg, and >100kg groups than for

the 80 - 86 kg group. Mean MT4 $\dot{V}CO_2$ was significantly greater for the 92 - 100 kg and >100 kg groups than for the 80 - 86 kg group. In addition, MT4 task $\dot{V}O_2$ increased with increasing body weight. Task $\dot{V}O_2$ was significantly lower for the Laddermill, Run, and Carry performed during MT4 than the steady-state $\dot{V}O_2$ reported by Kamon, *et al.* (1975) for those tasks. In conclusion, the significant differences in $\dot{V}O_2$ due to body weight observed in the present study indicate a potential for performance differences in respirators undergoing MT4 NIOSH certification testing. The present study provides data which may be appropriate for use in the development of a simulated MT4 ABMS test protocol.

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