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Reliability of cardiorespiratory measurements during wheelchair ergometry

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Abstract—The purpose of this research was to evaluate the stability of measures of heart rate (HR) and oxygen uptake ($\dot{V}O_2$) during repeated 30-minute bouts of constant work-rate wheelchair ergometry. Ten able-bodied subjects (seven male; three female) completed three sequential, single-stage wheelchair ergometer propulsion tests, to exhaustion, at least 48 hours apart, to determine the reliability of measurements of HR and $\dot{V}O_2$. Power output was determined as the resistance required to elicit 75% of the peak $\dot{V}O_2$ attained during a peak graded exercise wheelchair ergometer test, at a propulsion velocity of three miles per hour and a flywheel roll distance of 6.32 meters. The HR and $\dot{V}O_2$ measurements were averaged over the last 30 seconds of the first (T1) and second (T2) thirds of the tests and at volitional exhaustion (T3). Significant differences were not observed at any of the data points except for HR at exhaustion. The HR at exhaustion was lower for the third test than for the second test. Intraclass correlation coefficients for HR (R=0.92, 0.95, and 0.86) and $\dot{V}O_2$ (R=0.95, 0.96, and 0.97) were high across the three tests, at all of the data points, respectively. Coefficients of variation were generally low. The results of this study indicated that, with the exception of HR during exercise sustained longer than approximately 30 minutes, $\dot{V}O_2$ and HR measurements can be made with high reliability during sustained wheelchair ergometer propulsion.

Key words: *cardiorespiratory, test-retest reliability, wheelchair propulsion.*

INTRODUCTION

Measurement of wheelchair propulsion performance is critical to understanding functional capacity and potential for injury in manual wheelchair users. Routine wheelchair propulsion generally occurs at a percentage of one's maximum capacity. Wheelchair ergometers are often used to make measurements of wheelchair performance (1–6), because of the ease with which constant submaximal propulsion intensities can be sustained and to the ability to simulate wheelchair propulsion in a controlled environment. Constant work-rate endurance testing (CWRT) on the wheelchair

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ergometer has been used to determine biomechanical characteristics of the upper limbs (1) and cardiorespiratory responses (2) during propulsion. Rodgers et al. (7) used CWRT to identify potential etiologies for injury, based on differences in propulsion style in presymptomatic manual wheelchair users. Baldwin and associates (8) observed differences in force application to handrims in manual wheelchair users with and without median nerve abnormalities during CWRT. Performance and training studies have often involved nonwheelchair users in their analyses, a group of subjects that may introduce response variations because of their being unacclimated to the propulsion task (2,5,9–12). Applications such as these elucidate the importance of establishing intertest reliability of measurements obtained during CWRT.

The purpose of this study was to determine the reliability of measurements of cardiorespiratory function during CWRT. Nonwheelchair users were selected as subjects for this study because their wheelchair propulsion techniques are unpracticed and their fitness for sustained wheeling undeveloped. Given these factors, it was anticipated that there might be a high degree of variability in the measures of heart rate (HR) and oxygen uptake ($\dot{V}O_2$). It was hypothesized that cardiorespiratory response variations, as indexed by intertest differences in HR and $\dot{V}O_2$, would be observed across three CWRT tests in healthy nonwheelchair users.

METHODS

Subjects

Ten nonwheelchair users (height=178±10 cm, weight=79±15 kg, and age=31±7 years) were the subjects of this study. Seven were males and three were females. The criteria for inclusion were absence of upper-body orthopedic disorders, systemic diseases that would contraindicate participation by limiting upper-body exercise performance, and medications that would impede or enhance exercise performance. None of the subjects had been a user of a manual wheelchair for primary ambulation in the past and none had participated in an upper-body aerobic exercise training program in the past year. Prior to their participation, the purpose of the study, procedures, risks and benefits, and rights as a participant were explained verbally to each subject, and written consent was obtained in accordance with the procedures approved by the Institutional Review Board.

Apparatus

All exercise tests were carried out on a wheelchair ergometer prototype (**Figure 1**) described in detail elsewhere (2). The ergometer seat was adjusted in width to allow comfortable seating for each subject. Subjects sat in the wheelchair ergometer with their feet positioned on a step stool. Various sizes of stools were used to align the thigh in a position parallel to the floor, minimizing the use of the lower body for stabilization and mimicking leg positioning of manual wheelchair users in a wheelchair. The ergometer roller assembly consisted of a sprocket-chain system connecting an axle running between the wheels of the chair at one end and a flywheel at the other. The flywheel, a Monarch flywheel of standardized weight and circumference, was moved by subjects' application of torque to the handrims of the wheels. Flywheel resistance was applied by a nylon belt connected to the flywheel support at one end, wrapped around the flywheel, and wrapped around a pulley at the other end. Hang-weights were attached to a carriage connected to the pulley-end of the nylon belt for precise control of resistance applied to the flywheel. The functional roll distance of the flywheel was 6.32 meters for each complete turn of the handrims. Wheelchair propulsion velocity (32 rpm, equal to 3.0 km/hr) was maintained during testing by having subjects watch a digital speedometer attached to the right wheel of the chair. A telemetered pulse rate sensor and transmitter, attached by a belt to the thorax, and a receiver with a digital indicator (Polar Heart Rate Monitor) were used to obtain HR measurements. The $\dot{V}O_2$ measurements were made using breath-by-breath indirect calorimetry (Cardio2 Metabolic Measurement System, Medgraphics, St. Paul, MN), a system composed of rapid-response oxygen (zirconium cell) and carbon dioxide (infrared cell) analyzers, and a pneumotachometer, all interfaced with a microcomputer. Information from each breath was used to perform breath-by-breath Haldane transformations for the determintion of $\dot{V}O_2$. Inspired and expired volumes were determined from a flow-volume loop resulting from pneumotachometer differentiation. The timing of gas exchange and measurements made by the analyzers and pneumotachometer was coordinated in the analysis by continuous phase delay adjustments held to less than a ±2-percent error during the calibration process. Known concentrations of 21-percent oxygen and 0-percent carbon dioxide, and 12-percent oxygen and 5-percent carbon dioxide, both in nitrogen balances, were used to

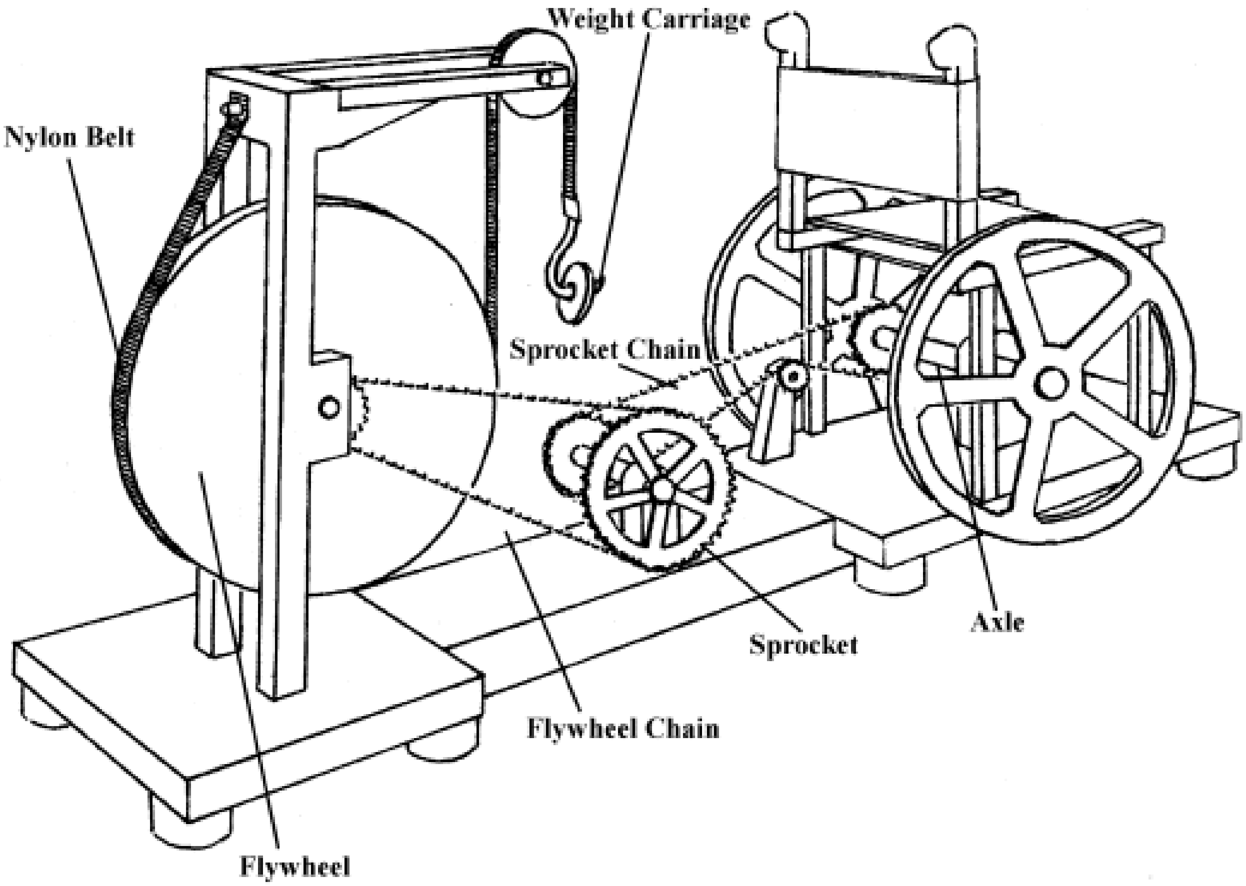

Figure 1.
Schematic view of the wheelchair ergometer. Labels denote main mechanical aspects for adjusting resistance and maintaining power output. Reprinted with permission. Keyser RE, Rodgers MM, Gardner ER, Russell PJ. Oxygen Uptake During Maximum Graded Exercise and Single Stage Fatigue Tests of Wheelchair Propulsion in Manual Wheelchair Users and the Able-Bodied. Arch Phys Med Rehabil 1999;80:1288–92.

calibrate the analyzers. Room air from a three-liter gas calibration syringe was used to standardize the pneumotachometer prior to each test. A 110-ml mouthpiece attached to respiratory-grade plastic tubing was used for subject interface.

Procedure

Peak Exercise Tests

Prior to the graded exercise test and at least 24 hours apart, subjects completed four 20-minute sessions of wheelchair ergometer propulsion, with minimal resistance, to adopt a propulsion style (7). Resting information was obtained following 6 minutes of quiet rest while sitting on the wheelchair ergometer. Subjects then propelled the wheelchair at a speed of 32 rpm as weight was incrementally added to the carriage. First, subjects propelled the ergometer with no weight placed on the carriage for 3 minutes. Then, while subjects maintained the target velocity, 0.3 kg of weight was added every 3 minutes. The addition of weight continued over time until the subjects were unable to maintain the required propulsion velocity. Subjects were verbally encouraged to maintain the target velocity. Raw breath-by-breath data reduction was reported in 30-second averages.

Constant Work-Rate Test

Subjects completed three CWRT tests at least 48 hours, but not more than 1 week, apart. The first in the order of these tests was completed at least 2, and not more than 7 days, after the peak test. Tests were performed at a similar time of day, within a range of plus or minus 2 hours. All CWRT were completed in the following manner. First, resting information was obtained in a manner similar to that preceding the peak tests.

Next, subjects completed a freewheeling interval by propelling the wheelchair ergometer for 3 minutes without weight added to the carriage at the 32-rpm propulsion velocity. Then, weights were added to the carriage, corresponding to the amount that elicited 75 percent of the peak $\dot{V}O_2$ attained on each subject's peak test. The ergometer was propelled until subjects were unable to sustain the target velocity. As in the peak test, strong verbal encouragement was offered to maintain the designated propulsion velocity. Breath-by-breath cardiorespiratory information was recorded as 30-second averages.

Statistical Analysis

The dependent variables for this study were HR, $\dot{V}O_2$, carbon dioxide expiration ($\dot{V}CO_2$), and pulmonary expired volume ($\dot{V}e$). The first independent variable was time of acquisition with classes identified as rest (R), during freewheeling (F), first third of test (T1), second third of test (T2), and last third of test or volitional exhaustion (T3). The time interval for T1 was determined as one-third of the total exercise time minus the time at which the weight was added to the carriage (9 minutes). The time interval for T2 was determined as two-thirds of the total test time minus 9 minutes. The time interval for T3 was determined as the total test time minus 9 minutes. Data points for T1, T2, and T3 were averages of the dependent variable scores over the last 30 seconds of the interval. The second independent variable was test, identified as Test-1, Test-2, and Test-3. Data were analyzed for significant differences in dependent variables across trials using treatment by subject, linear models analysis of variance (ANOVA). A separate ANOVA was used for each acquisition time to permit use of the subject (MSs) and within (MSw) mean squares to compute by-trial intraclass correlation coefficients (R) (13). Type-I error was accepted at 0.05 ($p<0.05$) for determination of a significant F-ratio. Scores are reported as means ± standard deviations throughout the text and tables.

RESULTS

Peak Exercise Test

Resting data and cardiorespiratory data for the peak test are listed in **Table 1**. Resistance observed at 75 percent peak $\dot{V}O_2$ was on the average 1.97±0.56 kg. Application of this weight to the carriage and maintenance of the 32-rpm propulsion speed resulted in an average power output of 65.2±18.6 watts. This weight was applied to the resistance carriage for all three submaximal tests.

Table 1.
Results of the peak wheelchair ergometer propulsion test.

	Rest	**Peak**
HR(bpm)	74±08	150±25
$\dot{V}O_2$(ml/min)	209±50	1555±375
$\dot{V}CO_2$(ml/min)	183±42	1767±469
$\dot{V}e$(l/min)	8.0±1.8	66.4±18.1

Data are means ± standard deviation.

The cardiorespiratory responses to the CWRT are described in **Table 2**. At T-3, HR was significantly higher ($p<0.04$) for Test-2. No other significant test-retest differences were observed. Coefficients of variation (CV) are presented in **Table 3**. The CV ranged from 0.10 to 0.40, with only Test-3 $\dot{V}CO_2$ at T-2, and Test-3 $\dot{V}e$ at T-1 and T-2 above 0.30. The CV were generally consistent across the tests, indicating interclass stability. A matrix of R is presented in **Table 4**. Of the 23 R-values, only R for $\dot{V}CO_2$ during unloaded freewheeling propulsion did not reach the 0.60 threshold for statistical significance. However, the significant F-ratio for HR at T-3 indicates that the intraclass association was the result of stable statistical difference rather than reproducibility. Among T-1, T-2, and T-3, intraclass coefficient of determination (R_2) indicates that between 6 percent and 27 percent of the total variance was due to intraclass variation in scores (**Table 4**). This finding indicates that the majority of the experimentwise variance in each dependent variable was found as intersubject variance. Therefore, the hypothesis of intertest difference in HR was supported only during sustained, prolonged propulsion of over 32 min. Otherwise, HR, $\dot{V}O_2$, $\dot{V}CO_2$, and $\dot{V}e$ were reproducible across the three CWRT tests.

DISCUSSION

Reliability of peak HR and $\dot{V}O_2$ responses to arm exercise has been reported. Keyser et al. reported similar peak HRs for three arm-ergometer tests using differing cranking speeds (14). However, some of these subjects were taking beta blockers at the time of the test. Another study revealed similar peak HR and $\dot{V}O_2$ when arm-cranking speeds of 60 and 70 rpm were used, but peak HR was significantly reduced when a cranking speed of 30 rpms was used (15). Theisen and associates (11) used

Table 2.
Results of constant work rate tests.

	Rest	FW	T-1	T-2	T-3
Test-1					
HR (bpm)	77±13	90±18	136±19	146±19	144±15
$\dot{V}O_2$(ml/min)	297±51	475±55	1234±275	1305±311	1297±295
$\dot{V}CO_2$(ml/min)	189±51	423±41	1396±391	1393±395	1315±364
$\dot{V}$e(l/min)	8.4±1.9	16.2±2.7	48.0±11.0	52.2±14.8	51.2±15.2
Time (min)	6	9	20.1±6.2	31.6±12.2	42.9±18.2
Test-2					
HR (bpm)	76±14	91±18	137±18	146±19	148±20*
$\dot{V}O_2$(ml/min)	223±51	492±57	1230±257	1268±293	1302±316
$\dot{V}CO_2$(ml/min)	205±65	454±54	1364±305	1345±366	1345±378
$\dot{V}$e(l/min)	8.8±2.6	17.2±3.2	47.2±9.9	50.7±14.1	52.4±19.8
Time (min)	6	9	20.8±8.0	33.1±16.1	45.2±24.2
Test-3					
HR (bpm)	83±14	93±20	132±21	139±20	136±15
$\dot{V}O_2$(ml/min)	215±45	513±102	1193±270	1237±331	1298±311
$\dot{V}CO_2$(ml/min)	186±47	458±111	1322±395	1308±440	1337±322
$\dot{V}$e(l/min)	8.4±1.9	17.8±3.4	48.3±15.3	52.4±21.0	54.8±13.3
Time (min)	6	9	20.2±5.9	32.0±12.0	43.6±17.8

Data are means ± standard deviations. Data are reported at rest and during freewheeling (FW), the first (T-1), second (T-2), and third (T-3) data acquisition intervals. Minutes 1–6 were at rest, minutes 6–9 were FW, and times for T-1 through T-3 were actual test time (interval +9 min). * significantly higher than T-3 on Test 3 ($p<0.04$).

Table 3.
Coefficients of variation around central tendency of scores by data acquisition point.

	Rest	FW	T-1	T-2	T-3
Test-1					
HR (bpm)	0.17	0.20	0.14	0.13	0.11
$\dot{V}O_2$	0.25	0.12	0.22	0.23	0.23
$\dot{V}CO_2$	0.27	0.10	0.28	0.28	0.28
$\dot{V}$e	0.23	0.17	0.23	0.28	0.34
Test-2					
HR (bpm)	0.18	0.20	0.13	0.13	0.14
$\dot{V}O_2$	0.23	0.11	0.21	0.23	0.24
$\dot{V}CO_2$	0.27	0.10	0.22	0.27	0.28
$\dot{V}$e	0.30	0.19	0.21	0.28	0.38
Test-3					
HR (bpm)	0.17	0.22	0.16	0.14	0.11
$\dot{V}O_2$	0.21	0.20	0.23	0.27	0.24
$\dot{V}CO_2$	0.25	0.24	0.30	0.34	0.24
$\dot{V}$e	0.23	0.19	0.32	0.40	0.24

interclass methods and reported reliability of peak HR, $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}$e, and blood lactic acid concentration in a group of nonwheelchair users using a wheelchair ergometer. Using interclass analyses, Bhambhani and associates found test-retest reliability of peak HR, $\dot{V}O_2$, and $\dot{V}$e to be high in two subjects with paraplegia and five subjects with tetraplegia resulting from spinal cord injuries (16). Janssen and associates reported high intraclass R-values for peak HR and $\dot{V}O_2$ (0.96 and 0.94, respectively) in two subjects with tetraplegia and eight subjects with paraplegia using wheelchair propulsion on a motor-driven treadmill (17). Bhambhani et al. found high test-retest reliability of peak $\dot{V}O_2$ and HR for wheelchair ergometer propulsion in athletes with cerebral palsy (18). Other

Table 4.
Coefficients of variation around central tendency of scores by data acquisition point.

	Rest		FW		T-1		T-2		T-3	
	R	R2	R	R2	R	R2	R	R2	R	R2
HR	0.69	0.48	0.96	0.92	0.92	0.85	0.95	0.90	0.86+	0.73
$\dot{V}O_2$	0.86	0.74	0.79	0.62	0.95	0.92	0.96	0.92	0.97	0.94
$\dot{V}CO_2$	0.71	0.50	0.43*	0.72	0.96	0.90	0.95	0.90	0.96	0.92
$\dot{V}e$	0.90	0.81	0.85	0.72	0.91	0.83	0.94	0.88	0.46	0.85
Time	—	—	—	—	0.86	0.73	0.86	0.73	0.87	0.76

* Nonsignificant. + Significant R accompanied by a significant F-ratio. R- and R^2-values are coefficients for the three submaximal tests at rest and during free-wheeling (FW), and the three data acquisition intervals (T-1, T-2, and T-3).

studies have reported high test-retest reliability for peak $\dot{V}O_2$ and HR using treadmill exercise in nonwheelchair users (19–23). No other studies of submaximal wheelchair propulsion reliability were found. Differences in the cardiorespiratory response patterns to CWRT have been reported. In a previously published manuscript (24), responses of the subjects of the current study, and on the current protocol, were compared to responses of manual wheelchair users. The manual wheelchair users appeared to sustain a similar power output at a higher oxygen cost, even though the test duration was similar among groups. High reliability for CWRT is important, since submaxima activity presents more opportunity for intraindividual variance, and submaximal propulsion protocols are often used to evaluate wheelchair propulsion performance. Gaps in the literature remain, related to reliability of these measures with specific reference to manual wheelchair users and important points of homogeneity.

Studies using both wheelchair ergometry (1) and wheelchair propulsion on a motor-driven treadmill (17) have yielded peak HRs that were similar to the age-predicted maximum values in manual wheelchair users. However, in agreement with the current study, Theisen and associates reported peak HR that was lower than the age-predicted maximum in nonwheelchair users (11). In the current study, peak HR appeared to be lower in these nonwheelchair users than in manual wheelchair users in other studies (1,17). In Test-1 and Test-2, HR approached the peak HR attained during the peak exercise test. At a submaximal load of 2,500 grams, Rodgers et al. reported a mean submaximal HR of 147 bpm in manual wheelchair users of an age similar to that of the nonwheelchair users in the current study (1). This response was similar to HR at T-2 and T-3, during Test-1 and Test-2 of the current study. The HR in Test-3 was 8 to 15 bpm lower than the mean HR reported by Rodgers et al. (1). Physical conditioning and task acclimation may alter test results. But, unless acclimation produces large changes in the movement pattern during propulsion, physiological variables such as HR and $\dot{V}O_2$ tend to be unaffected. Exercise training may result in decreased HR at a given PO. Several weeks of routine participation in an exercise program of moderate intensity and duration are usually needed to result in cardiorespiratory improvements. It is doubtful that a physiological training effect occurred after only two sessions of loaded wheelchair propulsion. Psychological stress may have been lessened after Test-2, resulting in a lower HR during loaded propulsion at T-3 during Test-3. Janssen and coworkers found that HR responses to activities of daily living, such as transfer from a wheelchair to a toilet seat and shower seat, and curb ascent, were reliable across three trials in subjects with paraplegia (24). Although these were nonsteady-state activities, the activities of daily living were of short duration and therefore in agreement with te findings of the current study, in as much as HR was determined to be a reliable measure, provided the duration of the activity is not prolonged.

Measurement of peak $\dot{V}O_2$ has been determined to be reliable in nonwheelchair users (11) and in manual wheelchair users (16,17). Peak $\dot{V}O_2$ in this study was similar to that observed in other studies in nonwheelchair users (11), as well as manual wheelchair users (1,6,9,10,16,17). Reliability was established for measurements of $\dot{V}O_2$ during CWRT. The $\dot{V}O_2$ during CWRT was, on the average, 81 percent of the peak $\dot{V}O_2$, slightly higher than expected, since the resistance was set as the weight corresponding to 75 percent of the peak $\dot{V}O_2$. The $\dot{V}CO_2$ was 75 percent of peak $\dot{V}CO_2$ value, and $\dot{V}e$ was 76 percent of the peak $\dot{V}e$ value. These findings were similar to those expected. The $\dot{V}CO_2$ is often used in calculations determining substrate utilization and substrate-level metabolic supplementation during sustained aerobic activity, underscoring the importance of its reliability. The $\dot{V}e$ is a general index of pulmonary function during activity, which is often used in the determination of breathing economy, making the repeatability of its measurement necessary.

CONCLUSION

The hypothesis that HR variability would be observed during the three tests was supported only during the longest measurement interval. In all other cases the null hypothesis was not rejected. The $\dot{V}O_2$, $\dot{V}CO_2$, and $\dot{V}e$ were found to be reproducible over the three tests at all data acquisition points. The HR measurements were reproducible as long as the propulsion time was not prolonged. Additionally, the findings indicate that $\dot{V}O_2$, $\dot{V}CO_2$, and Ve are reliable measurements during CWRT. The results of this study may be delimited to nonwheelchair users, since it is possible that the HR variation observed during prolonged wheelchair propulsion in these subjects may not be observed in subjects who are manual wheelchair users.

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