

Randomized controlled trial of Micro-Mobile Compression[®] on lactate clearance and subsequent exercise performance in elite male cyclists

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Background: The purpose of this paper was to assess the feasibility of Micro-Mobile Compression[®] (MMC) on lactate clearance following exhaustive exercise and on subsequent exercise performance.

Methods: Elite male cyclists were randomized to MMC (n = 8) or passive recovery (control, n = 8). MMC is incorporated into a sandal that intermittently compresses the venous plexus during non-weight bearing to augment venous return. On day 1, subjects performed a graded exercise test on a cycle ergometer followed by 60 minutes of seated recovery, with or without MMC. Blood lactate concentration ([La⁻]) was measured during exercise and recovery. Subjects returned home for 3 more hours of seated recovery, with or without MMC. On days 2 and 3, subjects exercised to exhaustion in a fixed-load cycle ergometer test at 85% peak power and then repeated the day 1 post-exercise recovery procedures. Lactate clearance data after the time to exhaustion tests on days 2 and 3 were averaged to adjust for interday variation.

Results: On the day after MMC or control recovery, mean time to exhaustion was 15% longer (mean difference, 2.1 minutes) in the MMC group ($P = 0.30$). The standardized mean difference of MMC for time to exhaustion was 0.55, defined as a moderate treatment effect. Following the graded exercise test, area under the 60-minute lactate curve was nonsignificantly lower with MMC (3.2 ± 0.4 millimolar [mM]) versus control (3.5 ± 0.4 mM, $P = 0.10$) and times from end of exercise to 4mM and 2mM were 2.1 minutes ($P = 0.58$) and 7.2 minutes ($P = 0.12$) shorter, although neither achieved statistical significance. Following time to exhaustion testing, the area under the 60-minute lactate curve was lower with MMC (3.2 ± 0.2 mM) versus control (3.5 ± 0.2 mM, $P = 0.02$) and times from end of exercise to 4mM and 2mM were 4.4 minutes ($P = 0.02$) and 7.6 minutes ($P < 0.01$) faster. The standardized mean difference of MMC on most lactate clearance parameters was >0.8 , defined as a large treatment effect.

Conclusion: MMC yields large treatment effects on lactate clearance following high-intensity exercise and moderate treatment effects on subsequent exercise performance in elite male cyclists.

Keywords: cycling, graded exercise test, recovery, time to exhaustion, venous return

Introduction

Strenuous exercise elicits important stresses on the musculoskeletal system and metabolic functions that can impair subsequent exercise performance and interfere with training practices. Fluxes in muscle cell metabolites associated with energy utilization during heavy exercise (eg, lactate) can delay recovery, influence muscle glycogen reserves, and, in some circumstances, contribute to transient decreases in subsequent exercise performance. Active recovery is a highly beneficial and advantageous training strategy compared with passive recovery since augmented post-exercise circulation

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encourages lactate clearance and, in some cases, may enhance subsequent exercise performance.¹⁻⁷ Recent studies have reported mixed findings on exercise performance following active recovery with compression garments⁸⁻¹¹ or whole body vibration.¹²⁻¹⁴ Additionally, compliance with compression garments is generally poor⁹ and the availability of whole body vibration units is limited to research use.

Micro-Mobile Compression[®] (MMC) is a novel technology that simulates the effects of active recovery by augmenting blood flow through the deep veins of the leg via cyclic pressure pulses to the plantar venous plexus. The platform for MMC is a sandal that provides cyclic compression to the arch of the foot when the user is in a non-weight bearing position. Dohm et al¹⁵ reported that MMC augmented blood flow velocity 12-fold above resting levels in the posterior tibial vein and four-fold above resting levels in the popliteal vein of healthy adults. A distinct theoretical advantage of MMC is that post-exercise circulation and lactate clearance may be augmented without the deleterious effects of decreased glycogen resynthesis in type I muscle fibers,¹⁶ lower muscle reoxygenation rates,¹⁷ and declines in subsequent exercise performance^{17,18} that have been reported in some studies of traditional exercise-based active recovery. The hypothesis of this randomized, controlled trial was that MMC would allow for enhanced clearance of blood lactate immediately following exhaustive exercise and an improvement in subsequent high-intensity, fixed-load exercise performance.

Materials and methods

Subjects

This prospective, randomized, controlled trial was conducted at the Human Performance Laboratory of the Anschutz Health and Wellness Center at the University of Colorado School of Medicine, Aurora, CO, USA. All study procedures were conducted in accordance with the Declaration of Helsinki and in accordance with a predefined protocol that was approved by all researchers and the Colorado Multiple Institutional Review Board. All participants gave informed consent before any study procedures were performed.

Eligible subjects were 16 elite (Pro/category 1/category 2) male road cyclists, aged 21–42 years. Consecutive eligible subjects were randomly assigned to MMC or passive recovery only (control) using a computerized random-number generator with a 1:1 allocation ratio and a block size of four. Treatment assignments were hidden from investigators and subjects via sealed and secured envelopes until each subject was randomized. Blinding of interventions was not feasible in this study.

Interventions

Cycle ergometry graded exercise test

Subjects were instructed to have adequate sleep the night before the test and to avoid food, alcohol, tobacco, and caffeine within 3 hours of the test. Each subject was provided with nutrition recommendations for the 3 days prior to exercise testing as well as during the 3-day experimental period. The dietary recommendations were consistent each day, and included complete abstinence from alcohol and consumption of a diet with 70% of calories from carbohydrate, 15% from protein, and 15% from fat.

Subjects performed a graded exercise test to exhaustion on a calibrated, electrically braked cycle ergometer (Lode Excalibur Sport, Lode, Groningen, The Netherlands) on day 1. Subjects performed an incremental test according to our protocol,¹⁹ which was slightly modified for this study. The initial workload was 2 W/kg, with increments of 0.5 W/kg every 3 minutes until volitional exhaustion. Maximal oxygen consumption ($\text{VO}_{2\text{max}}$), blood lactate concentration ($[\text{La}^-]$), heart rate, and power output were measured during the graded exercise test. Oxygen consumption (VO_2), carbon dioxide production (VCO_2), ventilation, and respiratory exchange ratio were determined through indirect calorimetry (ParvoMedics TrueOne 2400 Metabolic Measurement System, ParvoMedics Inc, Sandy, UT, USA). Criteria for attainment of $\text{VO}_{2\text{max}}$ included two of the following: respiratory exchange ratio >1.1 , maximal heart rate within 10 beats per minute of the calculated value, or an O_2 plateau (<50 mL per minute) with an increase in power output. Heart rate was continuously monitored with a heart monitor (Polar S725x, Polar Electro, Kempele, Finland). At the end of each stage, a sample of capillary blood (25 μL) from the earlobe was collected to analyze both intracellular and extracellular levels of L-lactate (YSI 1500 Sport, YSI, Yellow Springs, OH, USA).

Time to exhaustion

On days 2 and 3 at the same time of day, subjects performed a fixed-load exercise test at 85% of peak power output (power output_{peak}) determined on day 1, on the electrically braked cycle ergometer. Pretest procedures were identical to those of the graded exercise test. Subjects were requested to maintain the prescribed power output during exercise until volitional exhaustion. Gas exchange and heart rate were measured identically to day 1. $[\text{La}^-]$ was measured only at the end of exercise.

Exercise recovery procedures

On each of the 3 days after the exercise tests were completed, subjects recovered by sitting barefooted in the laboratory

for 60 minutes, with or without MMC. Blood was collected at 10-minute intervals throughout the 60-minute recovery period. Participants ingested a sports drink containing 1.5 g/kg of carbohydrates during recovery. Thereafter, subjects returned to their residences and immediately completed an additional 3 hours of seated passive recovery, with or without MMC. The post-exercise recovery procedures were identical on each day.

Micro-Mobile Compression

The MMC device (AVEX, LLC, Grand Junction, CO, USA, Figure 1) consists of a motorized thrusting arm and pressure pad powered by a long-lasting rechargeable battery. The unit is user-activated by depressing a power switch on the body of the motor, which is housed in a hollow within the sole of a custom sandal. Upon activation, the device thrusts an 18.6 cm² pressure pad directly onto the sole of the foot, compressing the plantar venous plexus. The MMC device adjusts the height of its thrust until the exerted pressure on the arch of the foot reaches a measured force of 3.76 N/cm². The thrusting pad remains pressed on the arch of the foot for 2 seconds before retreating to its resting position. This thrust-pause-retreat cycle repeats every 20 seconds while the wearer is non-weight bearing. A pressure-sensitive interrupt switch is activated if the wearer stands up. The MMC device returns to its cyclical thrusting rhythm after 60 seconds of wearer inactivity.

Data analysis

Lactate clearance data after the time to exhaustion tests on days 2 and 3 were averaged to adjust for interday variation²⁰ and between-group comparisons were adjusted for peak lactate concentration using analysis of covariance. The correlation of time to exhaustion on days 2 and 3 was high ($r = 0.78$). The area under the lactate curve during the 60-minute post-exercise recovery period was computed using the trapezoidal rule described by Matthews et al.²¹ To calculate

the time needed for peak lactate to reach fixed markers of lactate clearance, individual blood [La⁻] values were plotted at each time point during the 60-minute recovery period using a smoothed curve fitting model (Microsoft Excel, 2010, Redmond, WA, USA). Two fixed time points on each plotted lactate clearance curve were identified, ie, the time for lactate concentration to decline from peak to 4 mM ([La⁻]_{4mM}) and 2 mM ([La⁻]_{2mM}), respectively.

Time to exhaustion data on days 2 and 3 were averaged to adjust for interday variation,²⁰ and values were assessed with analysis of variance to compare the MMC and control groups. Analysis of covariance was explored to assess the potential influence of baseline characteristics and graded exercise test data. None of these variables influenced the effect of treatment group on time to exhaustion and, therefore, unadjusted data are reported.

Statistical significance was set at $P < 0.05$. Continuous variables were reported as the mean \pm standard deviation. Baseline subject characteristics and graded exercise test data were compared using an independent-samples *t*-test. For each main outcome, the mean between-group difference and 95% confidence interval (CI) were calculated. The standardized mean difference was also calculated for each variable, defined as the between-group mean difference divided by the common standard deviation. For reference, a standardized mean difference of 0.2 is considered small, 0.5 is moderate, 0.8 is large, and 1.0 is very large.²² The sample size in this study allowed the detection of a standardized mean difference > 1.5 , assuming two-sided alpha = 0.05, statistical power = 80%, and a 1:1 allocation ratio. All statistical tests were performed using NCSS software, version 7.1.21 (NCSS, LLC, Kaysville, UT, USA).

Results

Subject compliance

All subjects completed the 3-day testing period, and compliance with the testing protocol and dietary recommendations



Figure 1 The Micro-Mobile Compression® device. External (left) and long-axis cross sectional (right) views. Activation switch and pressure pad in raised position shown in right panel.

was 100%. No discomfort or complications were reported in subjects allocated to MMC or control.

Subject characteristics

Subject characteristics included a mean age of 29 ± 5 (range 21–42) years, body mass index of 21.7 ± 1.9 kg/m², VO_{2max} of 60 ± 6 mL/kg per minute, and peak power of 349 ± 40 W. The MMC and control groups did not differ in baseline characteristics (Table 1) or in responses to the cycle ergometer graded exercise test (Table 2).

Time to exhaustion with high-intensity, fixed-load ergometry

On the day after exhaustive exercise followed by MMC or control recovery, mean time to exhaustion with high-intensity, fixed-load cycling was 15% greater (mean difference 2.1 minutes, 95% CI –2.1 to 6.3) in the MMC group (16.2 ± 4.9 minutes) versus control (14.1 ± 2.6 minutes), although statistical significance was not achieved ($P = 0.30$). The standardized mean difference of MMC on time to exhaustion was 0.55, representing a moderate effect.

Lactate clearance after graded exercise testing

Following the graded exercise test, the area under the 60-minute lactate curve was nonsignificantly lower with MMC (3.2 ± 0.4 mM) versus control (3.5 ± 0.4 mM, mean difference 95% CI –0.8 to 0.1 mM, $P = 0.10$), indicating somewhat faster lactate clearance with MMC (Figure 2). The mean time required for lactate concentration to fall from peak exercise to $[La^-]_{4mM}$ was 2.1 minutes shorter with MMC versus control (mean difference 95% CI –5.8 to 9.9 minutes, $P = 0.58$). Similarly, the mean time for $[La^-]$ to fall from peak exercise to $[La^-]_{2mM}$ was 7.2 minutes shorter with MMC versus control (mean difference 95% CI –2.0 to 16.4 minutes, $P = 0.12$, Figure 3). Despite the lack of statistically significant group differences, the standardized mean difference of MMC on lactate clearance parameters after graded exercise test

Table 1 Baseline subject characteristics

Variable	MMC (n = 8)	Control (n = 8)	P-value
Age (years)	29.4 ± 6.1	29.3 ± 4.9	0.96
Height (cm)	179 ± 4	178 ± 5	0.79
Weight (kg)	70.7 ± 6.3	67.5 ± 8.0	0.39
Body mass index (kg/m ²)	22.1 ± 2.0	21.2 ± 1.7	0.35
Body fat (%)	10.4 ± 1.8	11.1 ± 1.0	0.40

Note: Values are mean \pm standard deviation.

Abbreviation: MMC, Micro-Mobile Compression®.

Table 2 Exercise capacity measures from cycle ergometer graded exercise test

Variable	MMC (n = 8)	Control (n = 8)	P-value
VO_{2max}			
Absolute (L per minute)	4.3 ± 0.6	3.9 ± 0.3	0.08
Relative (mL/kg per minute)	61.0 ± 6.5	58.6 ± 5.7	0.44
PO (W)			
Peak	362 ± 45	337 ± 33	0.22
85% peak	307 ± 38	286 ± 28	0.22
PO (W/kg)			
Peak	5.1 ± 0.6	5.0 ± 0.4	0.62
85% peak	4.4 ± 0.5	4.3 ± 0.3	0.62
VO_{2max}/PO ([mL/kg per minute]/W)	11.9 ± 0.9	11.6 ± 1.2	0.49
$[La^-]_{Peak}$ (mM)	8.2 ± 1.3	8.5 ± 1.2	0.39

Note: Values are mean \pm standard deviation.

Abbreviations: PO, power output; $[La^-]$, blood lactate concentration; VO_{2max} , maximal oxygen consumption; MMC, Micro-Mobile Compression®.

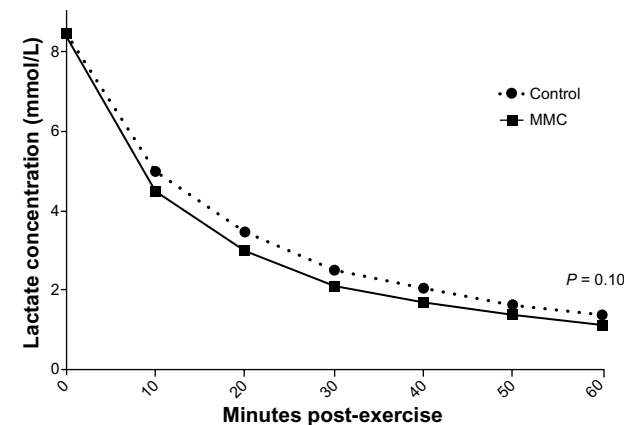


Figure 2 Area under the 60-minute lactate curve after graded exercise test. P-value represents the difference in 60-minute area under the lactate curve with MMC versus control. Plotted values are means.

Abbreviation: MMC, Micro-Mobile Compression®.

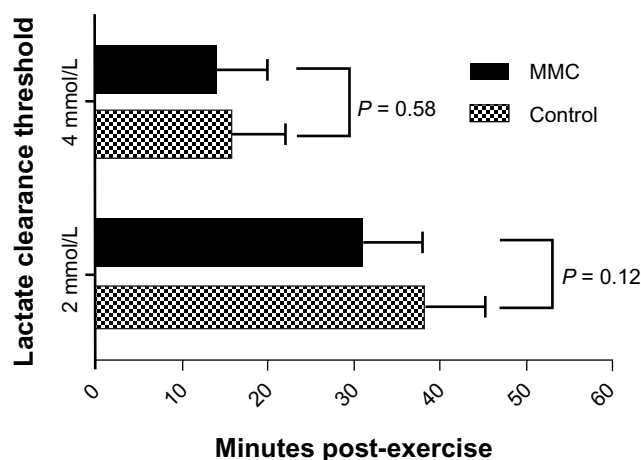


Figure 3 Lactate clearance time to 4 mM and 2 mM thresholds after graded exercise test. Values are means \pm 95% confidence intervals.

Abbreviation: MMC, Micro-Mobile Compression®.

was 0.88 (large effect) for the area under the 60-minute lactate curve, 0.29 (small effect) for time from peak to $[La^-]_{4mM}$, and 0.85 (large effect) for time from peak to $[La^-]_{2mM}$.

Lactate clearance after high-intensity, fixed-load ergometry

Following time to exhaustion testing, the area under the 60-minute lactate curve was lower with MMC (3.2 ± 0.2 mM) versus control (3.5 ± 0.2 mM, mean difference 95% CI -0.1 to -0.5 mM, $P = 0.02$, Figure 4). The time from peak to $[La^-]_{4mM}$ was 4.4 minutes faster with MMC versus control (mean difference 95% CI -0.9 to -7.9 minutes, $P = 0.02$) and time to $[La^-]_{2mM}$ was 7.6 minutes faster with MMC versus control (mean difference 95% CI -3.0 to -12.2 minutes, $P < 0.01$, Figure 5). The standardized mean difference of MMC on all lactate clearance parameters after time to exhaustion tests was >1.0 , representing very large effects.

Discussion

The major findings of this randomized, controlled trial are that application of MMC results in faster clearance of blood lactate following high-intensity exercise and yields moderate improvements in subsequent exercise performance in elite male cyclists. Although statistical significance was not achieved for all lactate clearance and performance parameters, calculated treatment effects were moderate to very large in most cases, despite the fact that the study was underpowered for some outcomes. This study represents the first published report on the potential applicability of MMC for enhancement of athletic performance.

Blood lactate testing is extensively utilized in the field of applied exercise physiology and sports performance.

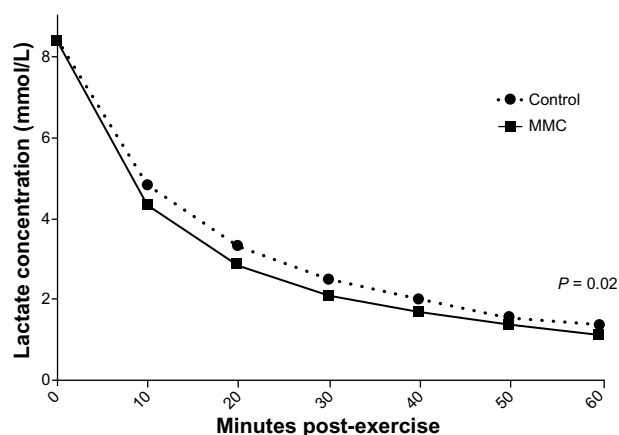


Figure 4 Area under the 60-minute lactate curve after fixed-load cycle ergometry at 85% peak power. P -value represents the difference in 60-minute area under the lactate curve with MMC versus control. Plotted values are means. **Abbreviation:** MMC, Micro-Mobile Compression®.

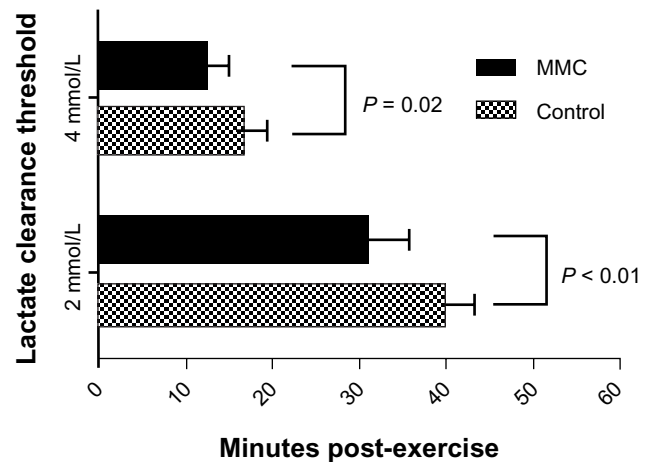


Figure 5 Lactate clearance time to 4 mM and 2 mM thresholds after fixed-load cycle ergometry at 85% peak power. Values are means \pm 95% confidence intervals. **Abbreviation:** MMC, Micro-Mobile Compression®.

It is well documented that highly trained athletes accumulate lower blood lactate levels,^{23–28} probably due to an enhanced lactate clearance capacity.²⁹ Lactate concentration at submaximal exercise intensities has discriminative ability to predict performance in competitive cyclists.¹⁹ Early in recovery, following high-intensity, fixed-load exercise that elicits high blood lactate accumulations, as in our study, enhanced lactate removal may aid recovery by a number of metabolic processes, including facilitating conversion to glucose in the liver and increasing substrate availability for many organs in the body, including the heart, brain, and less active skeletal muscle.^{29,30} Various types of active recovery following intense exercise have been shown to improve lactate removal.^{1–6,31–34} Further, active exercise recovery after strenuous exercise clears accumulated blood lactate in an intensity-dependent manner faster than passive recovery.³⁵ These effects are probably due to increased lactate efflux from active muscle, promoted by enhancing local blood flow and flow-related oxygen delivery, with little or no attendant increase in metabolic demand caused by the mode of active recovery employed. It is also plausible that effective forms of active recovery, in addition, may be instrumental in helping fatigued muscle shift metabolic processes more quickly in ways that shorten the time needed to replenish glycogen stores for heavy exercise training or competition on subsequent days.

Prior studies with MMC have yielded outcomes that are supportive of our findings. Dohm et al¹⁵ demonstrated that MMC yields venous velocity increases 12-fold above resting levels for the posterior tibial artery and four-fold for the popliteal artery, which were comparable with the peak venous velocities demonstrated with an intermittent

pneumatic compression system approved by the US Food and Drug Administration. Charles et al³⁶ compared MMC and below-knee graduated compression stockings on peak venous velocity at the popliteal vein. MMC yielded a four-fold increase in peak venous velocity versus no change for compression stockings. Based on the pronounced venous augmentation observed with MMC in these studies, the beneficial influence of MMC on lactate clearance in the current study was not surprising. In fact, all lactate clearance parameters in this study were associated with a large or very large standardized mean difference, with the exception of $[La^-]_{4mM}$ following the graded exercise test. Given that the time from peak lactate to $[La^-]_{4mM}$ was approximately 15 minutes, it is plausible that a greater duration of MMC is required to elicit maximal benefit on lactate clearance.

The exercise performance treatment effect in the current study was of such a magnitude to suggest moderate performance enhancement with exercise or competition on consecutive days, thereby warranting additional larger scale studies. However, the mechanism by which MMC influences subsequent exercise performance is unknown. Venous plexus compression is known to exert shearing stress on the endothelial lining yielding nitric oxide-mediated vasodilation,³⁷ which is known to regulate the microcirculation in upstream muscle³⁸ and to influence glycogen replenishment rates.³⁹ Animal studies demonstrate that intermittent pneumatic leg compressions improve exercise tolerance, in part, by enhancing blood flow to collateral-dependent tissues.⁴⁰ Additionally, muscle damage indices such as creatine kinase concentration⁴¹ and lymphatic outflow kinetics⁴² have been explored as possible mediators of exercise performance on consecutive days with compression clothing or devices. These markers are candidates for further study in order to determine the mechanism by which MMC influences subsequent exercise performance.

This study had several limitations worth mentioning. First, despite the promising lactate clearance outcomes with MMC over 60 minutes post-exercise, we did not assess exercise performance during this period. Instead, we focused on exercise performance the day after MMC, a design that is applicable to cyclists participating in intensive training on consecutive days or those competing in multiple-day stage races. Second, the sample size was sufficient only to detect large treatment effects compared with passive recovery. We therefore calculated the standardized mean difference of treatment effects to supplement formal hypothesis tests. Next, no formal comparisons with other active recovery methods were integrated into this study design. The results

of this study are generalizable only to competitive male cyclists and, therefore, extrapolation of the study outcomes to females or to non-cyclist endurance athletes should be done with caution. Finally, it is plausible that the wide range of subject ages may have confounded recovery from exercise, despite the fact that no differences in age were identified between groups.

Conclusion

This randomized, controlled trial demonstrated that MMC augments clearance of blood lactate following high-intensity exercise and moderately improves subsequent exercise performance in elite male cyclists. Larger, prospective, randomized, controlled trials are warranted to evaluate further the effect and mechanism of action of MMC technology on exercise performance and recovery.

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