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Kyoka Shimizu
Niigata University of Health and Welfare
Genta Ochi
ochi@nuhw.ac.jp

Niigata University of Health and Welfare
Yumi Okamoto
Niigata University of Health and Welfare
Tomomi Fujimoto
Niigata University of Health and Welfare
Koya Yamashiro
Niigata University of Health and Welfare

Case Report

Keywords: hair hormones, physical stress, athlete monitoring, case report, overtraining

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Additional Declarations: The authors declare potential competing interests as follows: The first author (KS) was also the sole participant in this study. This dual role is disclosed because it might be perceived as influencing her objectivity. The safeguards applied are described in the Methods. The authors declare no other conflicts of interest.

Hair cortisol covaried with a female collegiate long-distance runner's training volume over 22 months: A case report

Kyoka Shimizu,[1†] Genta Ochi,[1,2*†] Yumi Okamoto,[1,2] Tomomi Fujimoto,[1,2] Koya Yamashiro[1,2]

[1]Department of Health and Sports, Niigata University of Health and Welfare, Niigata, Japan

[2]Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, Niigata, Japan

***Correspondence:**
Genta Ochi
ochi@nuhw.ac.jp

[†]These authors contributed equally to this work and share first authorship.

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Abstract

Hair cortisol concentration reflects approximately one month of cortisol exposure and is associated with training and physical activity between individuals; however, it is unclear whether the relationship is present over monthly changes in training within one athlete. In this 22-month case report of one female collegiate long-distance runner, hair was sampled monthly and training volume was recorded as heart-rate-based energy expenditure. Correlations between hair cortisol concentration and training volume were calculated with lags of up to two months for hair cortisol concentration and other physiological markers (hair oxytocin concentration, waking heart rate, and heart rate variability). The analysis adjusted for menstrual status, seasonality, assay batch, and body mass. Significance testing was not conducted because successive monthly observations were not independent. Hair cortisol concentration was strongly correlated with training volume in the same month. The correlation was largest with no lag, even after a shared upward trend was removed, and remained strong after adjusting for each confounder. By contrast, the correlation between hair cortisol concentration and self-reported training load was weak, and other physiological markers were less closely associated with training volume. These findings suggest that hair cortisol concentration reflects training volume within an individual over a long period.

1. Introduction

A persistent imbalance between training load and recovery may result in maladaptation (Meeusen et al., 2013). A single saliva or blood sample captures a short-term snapshot of cortisol levels, whereas the proximal 1-cm hair segment approximates cumulative exposure over the preceding month (Short et al., 2016). Hair cortisol concentration has been positively associated with training volume in endurance athletes and vigorous physical activity in young adults (Gerber et al., 2013; Skoluda et al., 2012). Among female collegiate soccer players, it was positively associated with self-reported training

load (Sato et al., 2024), while changes were negatively associated with changes in vigor (Ohara et al., 2026). Tracking one person removes between-individual differences in covariates of hair cortisol (Stalder et al., 2017). However, season (Feneberg et al., 2025) and menstrual status may still vary within an individual.

Nevertheless, as these associations came from cross-sectional comparisons or two time points, they do not establish whether hair cortisol concentration tracks month-to-month changes in training within one athlete. This report describes one female collegiate long-distance runner over 22 consecutive months, with monthly hair sampling and heart-rate-based recording of every session. A distance runner was selected to ensure an objective training record. The primary aim was to describe how closely, and at what lag, hair cortisol concentration corresponded to monthly training volume, compared with other physiological markers and self-reported load, and after adjustment for each covariate. No generalization to other athletes is claimed.

2. Methods

2.1. Participant

The participant was a female collegiate long-distance runner (19–20 years old during the study) who competed in the Japan Intercollegiate Championships and was classified as Tier 2 (trained/developmental; McKay et al., 2022). She was a non-smoker and reported no chronic physical or mental health conditions at baseline. She is also the first author of this report.

Four safeguards addressed this dual role: physiological variables were recorded with objective instruments; psychological state was assessed using validated questionnaires on a fixed schedule; training followed her team coaches' plan, independent of the research group and unchanged by biomarker data; and the corresponding author alone handled, analyzed, and initially interpreted the data. She was not informed of the directional predictions and learned the results post data collection. The Ethics Committee of Niigata University of Health and Welfare approved this study, including her dual role (approval number 19366-240809). She provided written informed consent to participate and to the publication of data from an identifiable individual.

2.2. Study design

This observational case report comprised 22 consecutive monthly observations from September 2023 to June 2025 and was not preregistered. Hair samples were collected a median of 30 days apart (range 19–39 days) and treated as equally spaced. Reporting followed the CARE guidelines (checklist provided in the Supporting Information).

2.3. Measurements

Every training session was recorded using a chest sensor and sports watch (Polar H10 and Vantage V3; Polar Electro Oy, Kempele, Finland). Training volume (kcal/month), derived by the manufacturer's system from heart rate and duration, was the primary index; training time and distance were also recorded. Self-reported training load was calculated as monthly training duration multiplied by the session rating of perceived exertion (0–10).

A 1-cm segment (≈10 mg) cut from the scalp end at the posterior vertex indexed the preceding month, assuming growth of approximately 1 cm/month; thus, consecutive segments represented non-overlapping periods. She did not dye or bleach her hair during the study and washed it approximately twice daily. Samples were weighed, washed twice with isopropanol for 3 min, air-dried, and reweighed. An external laboratory (Air Plants Bio, Japan) measured cortisol and oxytocin using competitive enzyme-linked immunosorbent assay (pg/mg hair), as in previous studies (Ohara et al., 2026; Sato et

al., 2024). The three assay batches followed collection order; therefore, batch and study period could not be separated (Supporting Information). The mean intra-assay coefficient of variation for cortisol was 3.2%.

On three mornings during the fourth week of each month, heart rate and the root mean square of successive differences between inter-beat intervals (RMSSD) were recorded immediately after waking for 2 min supine (resting) and 2 min standing. Monthly values were calculated as means of three morning measurements.

Menstrual onset dates recorded in her training notebook were transcribed. Each month was coded for the presence or absence of menstruation (present in 15 months, absent in 7, including four consecutive months) and hormonal medication use (2 months). Body mass was measured monthly.

At each hair sampling session, she completed the Japanese version of POMS2 (Vigor-Activity and Fatigue-Inertia) and the six-item Kessler Psychological Distress Scale (K6). Race times over 5,000 m and 10,000 m were converted to World Athletics points; these measures are reported in the Supporting Information.

2.4. Data analysis

Analyses were conducted in R (version 4.4.2). We report correlation coefficients only; p-values, confidence intervals, multiplicity corrections, or significance thresholds are not presented. Successive monthly observations from one individual violate the assumption of independence. Coefficients of 0–0.3, 0.3–0.7, and 0.7–1.0 were interpreted as weak, moderate, and strong, respectively (Matsuura & Ochi, 2023; Ratner, 2009).

Hair cortisol concentration and training volume were cross-correlated at lags up to ±2 months under four specifications: interpolated, observed (21 months), first-differenced, and linearly detrended. Heart-rate-derived indices were unavailable for September 2023; hair cortisol concentration, self-reported training load, and body mass were available for all 22 months (Supporting Information). A positive lag indicates training volume leading hair cortisol concentration. The other markers (hair oxytocin, waking heart rate, and RMSSD) and self-reported training load were cross-correlated with training volume over the 21 observed months.

Concurrent correlations between hair cortisol concentration and training volume, time, distance, and self-reported load were computed, along with those between body mass, menstruation, and waking heart rate and both variables. Partial correlations between hair cortisol concentration and training volume were calculated by correlating residuals after separately regressing both on each covariate set: menstruation, menstruation plus hormonal medication, season (12-month sine and cosine), assay batch, and body mass.

3. Results

Over 22 months, hair cortisol concentration averaged 11.60 pg/mg (SD 4.79; range 3.86–21.71). Over 21 months, training volume averaged 13,911 kcal/month (SD 2,119; range 10,305–18,154). Descriptive statistics are presented in Table S1 and monthly series in Figures 1 and S1–S3.

The largest coefficient occurred at lag 0 in all specifications (Figure 2; Table S2): 0.761 interpolated, 0.756 observed, 0.496 first-differenced, and 0.667 linearly detrended. Concurrently, hair cortisol concentration correlated 0.756 with training volume, 0.450 with training time, 0.336 with training distance, and 0.116 with self-reported training load.

Five of six physiological markers, the largest absolute coefficient with training volume occurred at lag 0 (Table 1). The exception was hair oxytocin (lag −2, −0.305). Self-reported load peaked at lag +1 (0.521).

The concurrent correlation (0.756 unadjusted) was 0.716–0.810 after each adjustment (Table 2). Body mass correlated 0.280 and 0.009 with hair cortisol concentration and training volume, respectively; menstruation correlated 0.455 and 0.291, respectively. Mean hair cortisol concentration increased across the three batches (6.19, 12.11, and 15.57 pg/mg). It correlated 0.304 with K6, 0.131 with Vigor-Activity and −0.284 with Fatigue-Inertia (Tables S3–S5; Figure S4).

4. Discussion

This report examined whether monthly hair cortisol concentration covaried with training volume and found a strong same-month correlation (0.756). The coefficient was largest at lag 0 across all four specifications and remained strong after adjustment (0.716–0.810). In contrast, the correlation with self-reported training load was weak (0.116). These results suggest that hair cortisol concentration may serve as a biomarker of an individual's long-term physical activity (physical stress).

This association is consistent with between-person and two-time-point studies (Gerber et al., 2013; Sato et al., 2024; Skoluda et al., 2012), and was also observed within one athlete using monthly 1-cm segments. In contrast, Ohara et al. (2026) detected no significant change between two months despite increased self-reported load, possibly because they compared group means using self-reported load, which also correlated weakly here. Removing the shared upward trend reduced the coefficient to the moderate range (0.667 detrended; 0.496 first-differenced); however, lag 0 remained largest, while first-differenced coefficients one month either side were near zero (−0.004 and −0.035). This is consistent with the assumption that the proximal 1-cm segment integrates approximately the preceding month (Short et al., 2016).

Among the four measures of load, correlations with training time and distance were moderate. This difference from training volume is consistent with Gerber et al. (2013), who found a correlation with vigorous ($r = 0.34$) but not moderate activity ($r = -0.08$); heart-rate-based volume reflects intensity as well as duration. The weak correlation with self-reported load differs from Sato et al. (2024), who used repeated-measures correlations of hair cortisol across two time points, and from Balsalobre-Fernández et al. (2014), who collected salivary cortisol weekly. Session-RPE load also deviates from heart-rate-based load when training is predominantly low or high intensity (Borresen & Lambert, 2008). Accordingly, self-reported load correlated only 0.419 with training volume ($r = 0.91$ in Matsuura & Ochi, 2023). Because hair cortisol concentration correlated most strongly with training volume and most weakly with self-reported training load, the principal association does not depend on any values reported by the participant.

Waking standing heart rate (−0.519) and waking resting heart rate (−0.306) were lower in months with more training. A decrease in resting heart rate is classified as coping well with training unless prolonged (Buchheit, 2014), contrary to the possibility that stress-elevated heart rate inflated the heart-rate-based estimate of training volume. Training volume was negatively correlated with waking resting RMSSD (−0.212) and positively with waking standing RMSSD (0.328). Hair oxytocin concentration showed a weak positive coefficient (0.299), consistent with Ohara et al. (2026). Thus, among the measures collected after exercise, hair cortisol concentration most closely followed training volume.

Hair cortisol concentration was higher in months with menstruation (0.455), unlike the elevated serum cortisol in amenorrheic athletes (Loucks et al., 1989). In this case, months without menstruation included the month when both variables were lowest. Ohara et al. (2026) attributed their findings to lower winter and spring values, a pattern found in 10 of 15 between-person studies but only 2 of 14 within-person studies (Feneberg et al., 2025). Body mass correlated 0.280 with hair cortisol concentration but only 0.009 with training volume, suggesting the association is not attributable to body mass.

Exploratory correlations with mood were weak, while that with K6 was at the lower end of the moderate range. This is consistent with Sato et al. (2024), who interpreted hair cortisol concentration

as reflecting physical rather than mental stress, and with a meta-analysis (Stalder et al., 2017). In contrast, Ohara et al. (2026) found that hair cortisol concentration changes correlated negatively with changes in vigor, possibly because they analyzed changes across 22 players rather than values within one athlete.

This report has several limitations. First, findings from one athlete cannot be generalized to others. Second, the participant's dual role as first author could not be eliminated by design. Third, monthly sampling (19–39-day intervals) could not resolve delays shorter than one month. Fourth, menstrual records were retrospective and lacked cycle regularity and medication type and duration data. Fifth, although menstrual disturbance is one of several indicators used to assess relative energy deficiency in sport (Mountjoy et al., 2023), energy intake was not measured; therefore, whether the four consecutive months without menstruation reflected low energy availability could not be evaluated. Additionally, sleep and life events were not measured. Sixth, assay batch followed collection order and could not be separated from the study period. Seventh, sweat contains cortisol, and cortisol absorbed by hair from a hydrocortisone solution was not removed by isopropanol washing (Russell et al., 2014); thus, a contribution from sweat cannot be excluded. Finally, inter-assay variation for oxytocin was high, and hair growth rate was not verified.

5. Conclusion

Monthly hair cortisol concentration covaried with objectively recorded training volume over 22 months, most strongly at lag 0. The association remained strong after adjusting for potential confounders. Hair sampling, which requires neither a blood draw nor a device worn during training, may help track the preceding month's physical load.

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Ethics Statement

The study, including the dual role of the first author, was approved by the Ethics Committee of Niigata University of Health and Welfare (approval number 19366-240809), and all procedures were performed in accordance with the Declaration of Helsinki.

Informed Consent

The dual-role participant provided written informed consent both to participate in the study and to the publication of data obtained from an identifiable individual.

Conflict of Interest

The first author (KS) was also the sole participant in this study. This dual role is disclosed because it might be perceived as influencing her objectivity. The safeguards applied are described in the Methods. The authors declare no other conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions, because they comprise personal records of an identifiable individual who is also the first author. Requests will be answered with the consent of the author-participant and the approval of the Ethics Committee of Niigata University of Health and Welfare.

Code Availability Statement

The R script used for the analyses and figures (R version 4.4.2; base functions of the stats package and the zoo package) is available from the corresponding author on request.

Author Contributions

KS: Investigation, Writing – original draft. GO: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. YO: Supervision, Writing – review & editing. TF: Supervision, Writing – review & editing. KY: Supervision, Writing – review & editing.

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Declaration of Generative AI Use in Manuscript Preparation

Generative AI tools (Claude Opus 5.5) were used to translate the manuscript from Japanese into English.

able 1. Correlation coefficients between each marker and training volume across lags of −2 to +2 months (observed data only).

Marker	n	−2	−1	0	+1	+2
Hair cortisol concentration	21	0.287	0.513	0.756	0.491	0.163
Hair oxytocin concentration	21	−0.305	−0.158	0.299	0.091	0.159
Waking resting RMSSD	21	0.024	−0.007	−0.212	−0.013	0.161
Waking standing RMSSD	21	0.153	0.151	0.328	0.187	0.113
Waking resting heart rate	21	−0.092	−0.235	−0.306	−0.256	−0.167
Waking standing heart rate	21	−0.099	−0.071	−0.519	−0.371	−0.310
Self-reported training load	21	−0.147	−0.067	0.419	0.521	0.122

Note. Positive lags indicate that training volume precedes the marker. Lag 0 exhibited the largest absolute coefficient for five of the six physiological markers; for hair oxytocin concentration the largest absolute coefficient occurred at lag −2 (−0.305) rather than lag 0 (0.299), and for self-reported training load the largest coefficient occurred at lag +1 (0.521) rather than lag 0 (0.419). Concurrent correlations of hair cortisol concentration with the four measures of training were 0.756 (training volume), 0.450 (training time), 0.336 (training distance) and 0.116 (self-reported training load). RMSSD, root mean square of successive differences between heartbeats.

Table 2. Concurrent (lag 0) correlation between hair cortisol concentration and training volume, before and after adjusting for potential confounders.

Variable(s) controlled	n	r
None (zero-order)	21	0.756
Menstruation (present/absent)	21	0.734
Menstruation + hormonal medication	21	0.716
Seasonality (12-month sine and cosine)	21	0.743
ELISA assay batch	21	0.810
Body mass	21	0.779

Note. Partial correlations were obtained by regressing each series on the control variable(s) and correlating the residuals. The association remained strong ($r > 0.70$) following every adjustment.

Figure legends

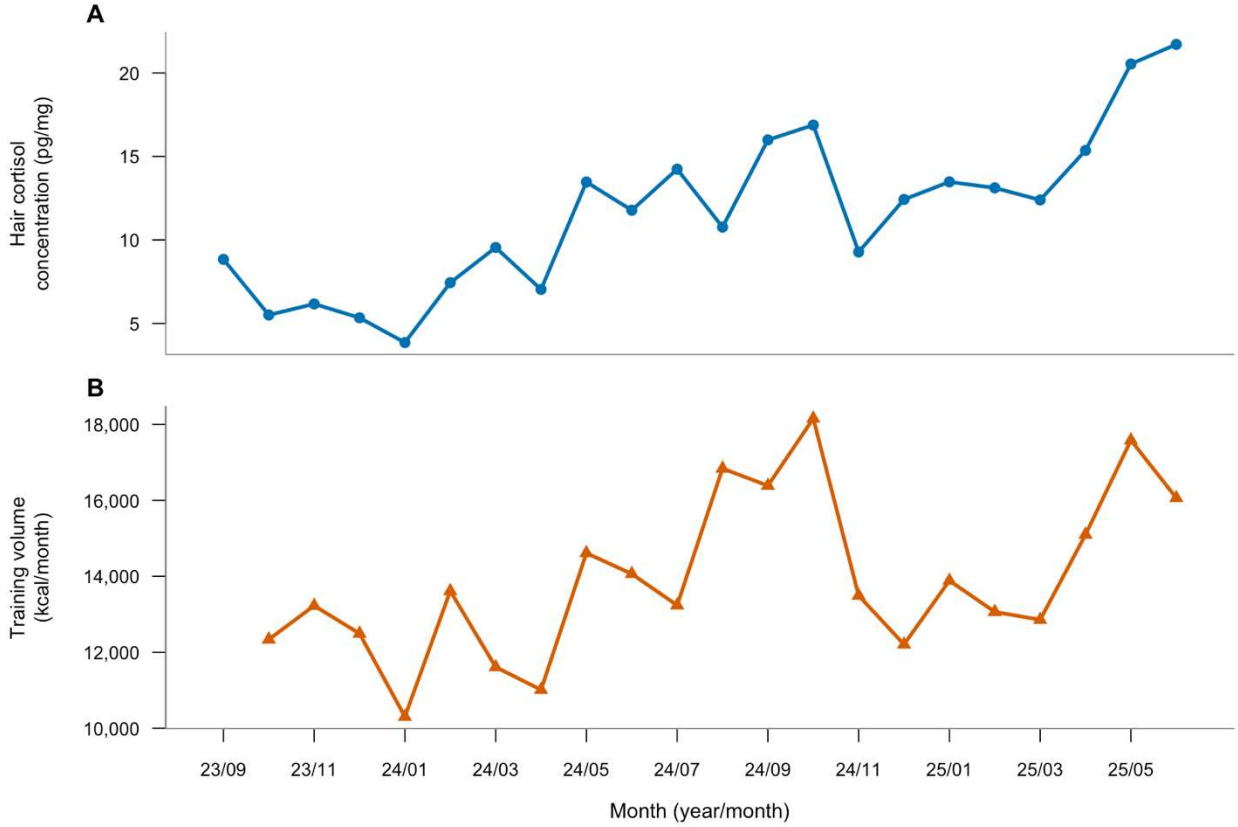


Figure 1. (A) Hair cortisol and (B) training volume monthly series, both of which trend upward over 22 months. Both were lowest in the same month (hair cortisol concentration 3.86 pg/mg; training volume 10,305 kcal). The highest hair cortisol concentration was recorded in June 2025 (21.71 pg/mg) and the highest training volume in October 2024 (18,154 kcal).

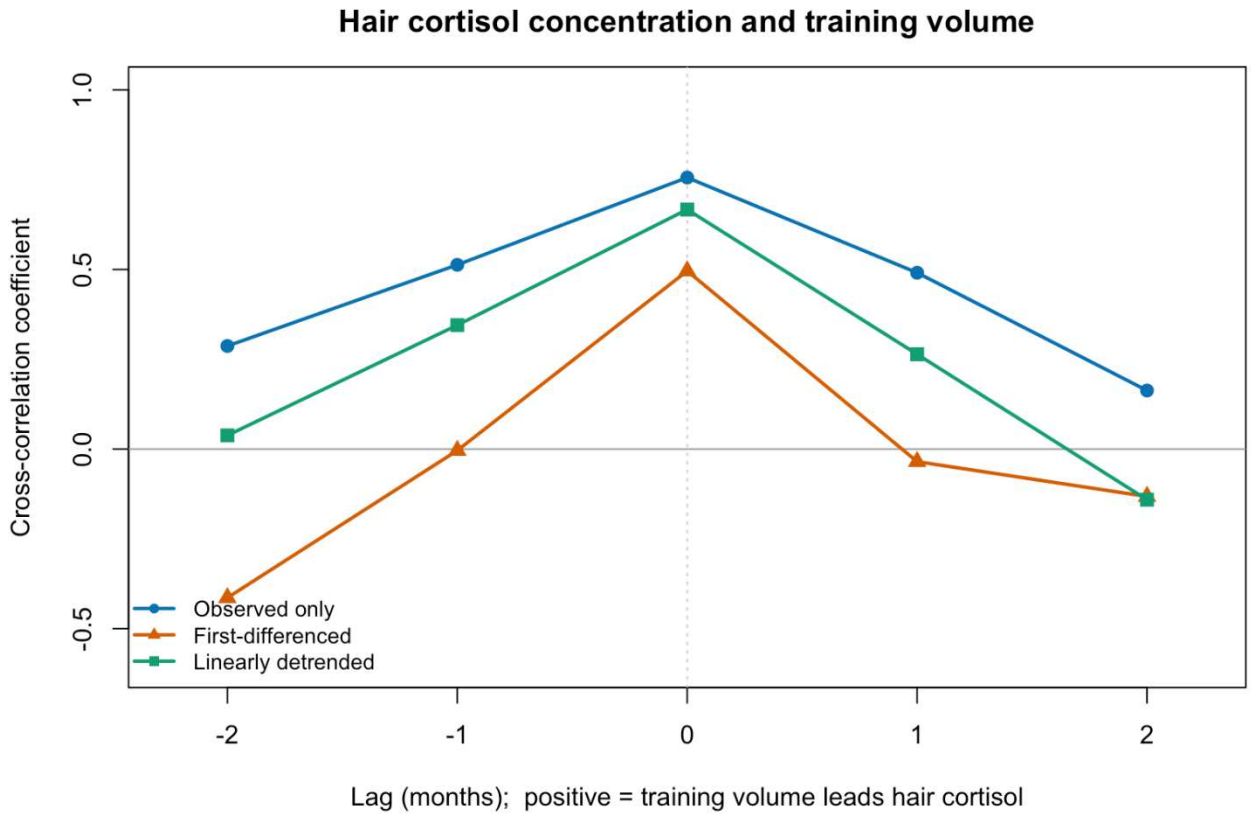


Figure 2. The shape of the lag profile differed among specifications. In the interpolated and observed series, the coefficients declined to c. 0.5 at one month in either direction (0.520 and 0.526; 0.513 and 0.491) and to 0.16–0.29 at two months. In the first-differenced series, from which the shared upward trend is removed, the coefficients at one month in either direction were close to zero (−0.004 with hair cortisol leading and −0.035 with training volume leading) while the coefficient at lag 0 was 0.496; at two months the coefficients were −0.414 with hair cortisol leading and −0.132 with training volume leading. In the linearly detrended series, the coefficients were 0.345 and 0.264 at one month in either direction and 0.038 and −0.141 at two months.

Supplementary Files

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