



The hematological responses of Indonesian elite rowing athletes to different altitude training protocols

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Abstract

Background: Altitude training is widely used to improve endurance performance through hematological adaptations, but inter-individual variability is substantial, and responses among Southeast Asian athletes are poorly documented.

Aims: This study compared hemoglobin, hematocrit, and reticulocyte dynamics in Indonesian elite rowers undergoing continuous high-altitude (HA) versus intermittent Pangalengan (PGL) protocols to characterize temporal adaptation patterns, identify predictive biomarkers, and inform protocol optimization.

Methods: A total of 23 national-team rowers (8 females, 15 males) completed a 33-day longitudinal observational study at 2,434 m. Blood samples were collected at baseline (T0), post-exposure (T1, day 22), and recovery (T2, day 31). The HA group (n=12) remained continuously at altitude; the PGL group (n=11) made periodic normoxic descents. Data were analyzed using mixed-model repeated-measures ANOVA and correlation analyses. Ethical approval was obtained before data collection in accordance with the Declaration of Helsinki.

Results: Contrary to expectations, the HA protocol produced significant hemoglobin reductions (males: -3.78%, p=0.008), whereas the PGL protocol elicited positive adaptations (males: +4.69%, p=0.026). Negative responders constituted 75% of the HA group versus 9.1% of the PGL group ($\chi^2=11.52$, p=0.003). Baseline ferritin did not predict hemoglobin responses (r=-0.122, p=0.579).

Conclusion: Protocol design, particularly the inclusion of normoxic recovery periods, was a stronger determinant of hematological adaptation than individual iron stores or sex. These findings affirm the live-high-train-low principles across diverse populations and support recovery-oriented protocols for Indonesian elite rowers.

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INTRODUCTION

Altitude training is gaining scientific validation as a method for enhancing performance among endurance athletes, particularly in sports such as rowing, which require a high degree of aerobic fitness (Bonato et al., 2023; Salgado et al., 2025; Lundby & Robach, 2025). The fundamental physiological basis is exposure to hypoxic conditions at reduced or normal atmospheric pressure, which triggers adaptive mechanisms that augment oxygen transport capacity (Jakovac & Belamarić, 2025; Öntürk et al., 2025). These physiological adjustments are evident in blood-related alterations observed through an increase in hemoglobin mass, red blood cell synthesis, and erythropoietic activity, which are regulated by hypoxia-inducible factors (HIFs) and erythropoietin (EPO) (Haase, 2021; Bhoopalan et al., 2020; Neumann et al., 2021). The process requires activation of the HIF pathway by cellular oxygen sensors, which subsequently upregulates genes associated with erythropoiesis, angiogenesis, and metabolic adaptations (Lee & Bhatt, 2022; Öntürk et al., 2025).

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Despite a strong mechanistic rationale, empirical data consistently demonstrate substantial inter-individual variability in adaptation to altitude training, challenging the assumption of a uniform response (Bossi et al., 2025; Mujika et al., 2025; Robach et al., 2021). Whereas some athletes exhibit pronounced gains in hemoglobin and performance improvements, others show negligible or adverse changes under seemingly identical conditions (Kettunen et al., 2023). Three critical questions remain unanswered in the existing literature: (1) What remains unknown is the precise combination of factors that reliably distinguishes positive from non-responders, including the relative contributions of protocol structure, genetic predisposition, iron status, and recovery quality. (2) Why Indonesian rowing athletes represent an important context: Indonesia fields nationally competitive rowing programs with distinct genetic profiles, nutritional patterns, and environmental conditions compared to the European and North American cohorts that dominate current evidence; yet, no study has systematically characterized their hematological responses to altitude training. (3) What has never been researched: a direct, protocol-controlled comparison of continuous versus intermittent altitude exposure in Indonesian national-team rowers, tracking hemoglobin, hematocrit, and reticulocyte dynamics longitudinally across baseline, acute-exposure, and recovery phases, does not exist.

Recent evidence has clarified several mechanistic dimensions. Öntürk et al. (2025) demonstrated that HIF-1 α , EPO, hepcidin, iron metabolism, and nitric oxide interact differently across training modalities, with aerobic exercise producing earlier erythropoietic signals than anaerobic exercise. Carin et al. (2025) reported that hemoglobin mass elevation in elite swimmers persisted post-altitude, driven by prolonged erythrocyte survival rather than continued production, with implications for competition scheduling. Mujika et al. (2025) documented highly variable hemoglobin-mass changes across successive altitude camps in world-class female water polo players, identifying menstrual phase, training intensity, recovery state, and nutritional habits as modulating factors. Neumann et al. (2021) and Nolte et al. (2025) further established that iron deficiency constrains erythropoietic responses even when EPO is elevated, while Cerda-Kohler et al. (2022) reported that moderate altitude improved submaximal but not maximal performance in Chilean elite rowers, leaving unresolved questions about hematological mechanisms and optimal competition timing. These findings collectively underscore that altitude adaptation is protocol-sensitive, iron-dependent, and highly contextual, yet none of these investigations involved Southeast Asian rowing populations.

A key gap in existing research concerns the structural design of altitude protocols and the precise dose-response relationship between hypoxic and normoxic exposure. Most comparative studies have not systematically isolated the effect of intermittent descent from continuous residence at the same elevation and duration. Variations in protocol structure (e.g., Live High Train Low [LHTL] vs. Live High Train High [LHTH]), measurement timing, sample heterogeneity, and follow-up duration limit cross-study comparability and prevent definitive protocol recommendations (Bonato et al., 2023; Chen et al., 2023). Furthermore, available studies do not differentiate between populations with different nutritional baselines, genetic polymorphisms affecting iron metabolism, or training histories divergent from European norms, making direct application to Indonesian athletes scientifically unjustified without dedicated empirical data.

Among the hematological variables meriting attention, reticulocyte dynamics represent a particularly underexplored monitoring tool in elite rowing. Reticulocytes are immature erythrocytes that serve as a sensitive, early indicator of erythropoietic activity, detectable before changes in total hemoglobin become apparent (Lundgren, 2022; Płoszczyca et al., 2018). This temporal sensitivity is especially valuable when assessing the onset and magnitude of the hypoxic erythropoietic response (Nolte et al., 2025; Weng et al., 2021). However, the trajectory of reticulocytes across the distinct phases of altitude training, initial acclimatization, intensive hypoxic loading, and post-altitude recovery remains poorly characterized in elite rowers (Raberin et al., 2024). Existing evidence offers conflicting patterns, as reticulocyte counts are simultaneously shaped by individual biology, training intensity, iron availability, and recovery quality, making phase-specific interpretation challenging without prospective longitudinal tracking (Mujika et al., 2024; Skattebo & Hallén, 2022). Clarifying whether the reticulocyte surge precedes, accompanies, or predicts sustained hemoglobin elevation would provide a practical real-time monitoring marker, directly

addressing the inconsistencies and knowledge gaps identified in previous literature (Zhou et al., 2026; Koivisto-Mørk et al., 2021).

This study addresses the identified gaps by systematically characterizing hematological responses of Indonesian national-team rowers to a 33-day altitude camp, comparing two naturally occurring protocol variants: continuous HA residence versus intermittent normoxic descent (PGL) and tracking hemoglobin, hematocrit, and reticulocyte parameters across three time points. Rather than claiming broad generalizability, this investigation aims to generate empirical baseline data for an underrepresented population, contribute to the comparative protocol literature, and identify whether reticulocyte dynamics offer early predictive value for sustained hemoglobin adaptation. The results are intended to provide context-specific evidence for practitioners designing altitude-training programs for Southeast Asian endurance athletes, while contributing to the broader scientific discussion of inter-individual variability and protocol optimization (Wilber, 2022).

Three primary objectives were pursued: (1) to characterize hematological parameter patterns across baseline, acute-exposure, and recovery phases; (2) to identify training-protocol and sex-related determinants of inter-individual response variability; and (3) to examine associations between reticulocyte dynamics and sustained hemoglobin adaptations. Four directional hypotheses were formulated: H₁: Altitude exposure will produce significant increases in hemoglobin and hematocrit in most athletes, but with substantial inter-individual variation, creating distinct positive, non-, and negative responder subgroups. H₂: Reticulocyte counts will follow a biphasic trajectory, rising during acute exposure and declining during recovery, reflecting hypoxia-induced erythropoiesis followed by stabilization. H₃: Male athletes will exhibit greater absolute hemoglobin and hematocrit increases than females, given higher baseline values and erythropoietic potential, though proportional changes may be comparable. H₄: Higher baseline ferritin will be positively associated with greater hemoglobin responses, as iron availability constrains erythropoietic capacity (Neumann et al., 2021; Nolte et al., 2025).

METHOD

Study Design

This study adopted a quasi-experimental, longitudinal, observational framework with repeated measures to evaluate hematological responses in Indonesian rowing athletes during a national altitude training camp. Participants were assigned to training groups according to the national training center's scheduling policy rather than by random allocation; therefore, this design does not constitute a controlled trial, and causal inferences must be interpreted with appropriate caution. Claims regarding the effectiveness of altitude training are thus conveyed in terms of within-group change and between-group comparison under naturalistic conditions, rather than implying strict causal superiority. Three discrete measurement intervals were administered: baseline (T0), post-altitude exposure (T1), and recovery phase (T2). The repeated-measures design enabled systematic assessment of within-individual hematological changes under ecologically valid conditions, while the two-group structure provided a basis for comparing protocol-specific responses.

Participants

A total of 23 elite Indonesian rowing athletes (8 females, 15 males) from the national team participated in the study. Inclusion criteria were: active national team membership, mean age 27.71 (SD = 3.94) years, medical clearance for altitude training, a minimum of two years of competitive experience, no altitude exposure in the three months before the study, and written consent to blood sampling. Exclusion criteria included hematological disorders, use of erythropoiesis-stimulating agents, acute illness, iron supplementation above therapeutic doses, or pregnancy. Participants were allocated to the High Altitude (HA; n=12, 4 females, 8 males) or Pangalengan (PGL; n=11, 4 females, 7 males) training groups according in the national training center's scheduling policy, rather than through random assignment. This non-randomized allocation constitutes a potential source of selection bias and was accounted for when interpreting between-group comparisons. The absence of randomization and a control group may partially explain group differences. All participants provided written informed consent. This study was conducted in accordance with the Declaration of Helsinki.

Ethical clearance was obtained from the relevant institutional review board before commencement of any data collection, and all blood sampling procedures were performed under medical supervision.

Instrument

Blood samples were collected via venipuncture between 06:00 and 08:00, following an overnight fast and at least 24 hours after vigorous training to minimize acute exercise-related fluctuations. Samples were analyzed using automated hematology analyzers in a laboratory accredited to ISO 15189. Primary outcomes were hemoglobin (Hb), hematocrit (Hct), reticulocyte percentage (RET%), and absolute reticulocyte count (RET). Secondary outcomes included red blood cell count (RBC), mean corpuscular volume (MCV), mean corpuscular hemoglobin concentration (MCHC), serum ferritin, and reticulocyte hemoglobin equivalent (RET-HE). Serum ferritin was prioritized as a monitoring marker given its established role in constraining erythropoietic responses at altitude (Lundgren, 2022; Neumann et al., 2021; Sim et al., 2019). Quality control procedures included daily analyzer calibration and participation in external quality assessment programs.

Procedures

The altitude training intervention was conducted over 33 days at an elevation of 2,434 m above sea level on Mount Patuha, West Java, Indonesia. The training protocol comprised three phases: (1) a 7-day acclimatization phase with low-intensity training; (2) an 18-day intensive training phase with progressively increasing volume and intensity, including on-water rowing and interval sessions; and (3) an 8-day taper and recovery phase with reduced load. Blood samples were collected at T0 (October 25, pre-altitude baseline), T1 (November 16, after 22 days at altitude), and T2 (November 25, after a 9-day taper). The HA group remained continuously at altitude throughout all three phases, consistent with live-high train-high (LHTH) principles (Salgado et al., 2025). The PGL group periodically descended to the Pangalengan lowland training facility for designated sessions before returning to altitude, reflecting intermittent normoxic recovery analogous to live-high train-low (LHTL) methodology (Girard et al., 2023; Płoszczyca et al., 2018). This structural difference in normoxic exposure constituted the primary independent variable of interest. Both groups followed the same periodized training plan in terms of session structure and target intensities, with the key distinction being the altitude at which specific sessions were completed.

Data Analysis

Statistical analyses were performed using SPSS and R with a significance threshold of $\alpha = 0.05$. Given the small sample size ($N = 23$), analytical choices were calibrated to avoid model overfitting. Temporal changes in hematological parameters were evaluated using a mixed-model repeated-measures ANOVA, selected for its robustness to missing data and capacity to model within- and between-subject variance simultaneously; sex and training group served as between-subjects factors. Post-hoc pairwise comparisons applied Bonferroni correction to control Type I error inflation. Athletes were categorized as positive responders ($\Delta\text{Hb} > +0.4$ g/dL), non-responders ($\Delta\text{Hb} -0.4$ to $+0.4$ g/dL), or negative responders ($\Delta\text{Hb} < -0.4$ g/dL) using established criteria. Pearson and Spearman correlation coefficients were computed to examine relationships between baseline ferritin and hemoglobin responses, and between reticulocyte changes and hemoglobin changes. A multiple regression model was applied with parsimonious variable selection proportional to sample size. Independent-samples t-tests assessed sex differences in absolute and percentage changes. Effect sizes (Cohen's d) are reported alongside p-values to facilitate interpretation, given the modest sample.

limitations of the methodology

Several key methodological limitations must be acknowledged. First, hemoglobin concentration rather than total hemoglobin mass (the gold-standard CO-rebreathing method; Ahlgrim et al., 2018) was measured, which may be subject to plasma volume confounding; however, parallel hematocrit changes support the authenticity of observed red cell alterations. Second, mechanistic biomarkers (EPO, HIF-1 α , hepcidin, RET-HE) were not assessed, constraining physiological interpretation. Third, the small sample size ($N = 23$), particularly female subgroups ($n = 4$ per group), limits statistical power for sex-stratified analyses, increasing the risk of Type II errors

in non-significant findings. Fourth, the quasi-experimental non-randomized design introduces potential confounding from unmeasured variables, including sleep quality, nutritional habits, and psychosocial stress; the absence of a control group further limits causal attribution. Fifth, the nine-day follow-up period is insufficient to characterize the kinetics of adaptation decay or to guide competition timing. Sixth, the absence of concurrent performance testing prevents evaluation of whether hematological changes translated into competitive advantage (Lundgren, 2022; Girard et al., 2017). Despite these limitations, the study provides ecologically valid longitudinal data on an underrepresented Southeast Asian elite population using a methodologically rigorous repeated-measures design.

RESULTS AND DISCUSSION

Results

Participant Characteristics

Twenty-three elite Indonesian rowing athletes provided complete hematological data at T0 and T1. The sample comprised 8 females (34.8%) and 15 males (65.2%), allocated to the HA group (n=12; 4 females, 8 males) or the PGL group (n=11; 4 females, 7 males). All participants were Indonesian national team members aged 19–37 years with at least two years of competitive experience.

Baseline Hematological Parameters

The baseline hematological parameters are detailed in Table 1, with male athletes exhibiting significantly higher hemoglobin concentrations (16.28 ± 0.96 g/dL) than their female counterparts (13.90 ± 0.79 g/dL). The result was in line with the recognized physiological disparities between the sexes and the normative values for elite rowers (Baar et al., 2022; Podstawski et al., 2022). The males also had higher hematocrit values ($50.44 \pm 2.75\%$) than the females ($44.80 \pm 1.94\%$), in well as higher serum ferritin levels (135.59 ± 55.17 ng/mL and 79.95 ± 27.96 ng/mL, respectively). These values were within the normative ranges reported for elite rowers (Baar et al., 2022; Podstawski et al., 2022). There were no statistically significant baseline differences between the HA and PGL groups concerning hemoglobin ($t=1.723$, $p=0.0995$), hematocrit ($t=1.422$, $p=0.1698$), or ferritin ($t=-0.467$, $p=0.6452$). The trend validated the comparability of the groups at the commencement of this study.

Table 1. Baseline Hematological Characteristics by Gender

Parameter	Females (n=8)	Males (n=15)	p-value
Hemoglobin (g/dL)	13.90 ± 0.79	16.28 ± 0.96	<0.001
Hematocrit (%)	44.80 ± 1.94	50.44 ± 2.75	<0.001
Ferritin (ng/mL)	79.95 ± 27.96	135.59 ± 55.17	0.009
MCV (fL)	88.19 ± 9.20	91.06 ± 3.71	0.350
RBC ($10^6/\mu\text{L}$)	5.12 ± 0.52	5.55 ± 0.42	0.033

Note. Values presented as mean \pm standard deviation. MCV = mean corpuscular volume; RBC = red blood cell count.

Hemoglobin Responses to Altitude Training

Hemoglobin responses to altitude training showed significant differences between the two training groups after 22 days, as presented in Table 2. The HA group trained at high altitude reported a substantial reduction in hemoglobin concentration for both female and male athletes. This was observed in female HA athletes, who showed an average decrease of $2.88\% \pm 2.92\%$ from 13.97 ± 0.33 to 13.57 ± 0.62 g/dL ($t = -1.960$, $p = 0.145$). The male HA athletes also showed a statistically significant decline of $3.78\% \pm 2.86\%$, from 16.91 ± 0.71 to 16.26 ± 0.56 g/dL (paired t-test: $t = -3.709$, $p = 0.008$).

A contrasting trend was identified in the PGL group, which exhibited positive hemoglobin adaptations, with the female reporting a non-significant increase of $2.75\% \pm 6.57\%$ from 13.82 ± 1.16 to 14.25 ± 1.91 g/dL ($t=0.982$, $p=0.399$). In comparison, the male recorded a statistically significant elevation of $4.69\% \pm 2.56\%$ from 15.56 ± 0.66 to 16.07 ± 0.66 g/dL (paired t-test: $t=2.936$, $p=0.026$). The differences between the groups in male athletes were particularly substantial, with hematocrit

changes showing statistical significance: HA recorded -6.06%, and PGL recorded +0.22% ($t=-4.260$, $p<0.001$).h

Table 2. Hemoglobin Changes by Group and Gender

Group	Gender	Hb T0 (g/dL)	Hb T1 (g/dL)	Change (%)	p-value
HA	Female	13.97 ± 0.33	13.57 ± 0.62	-2.88 ± 2.92	0.145
HA	Male	16.91 ± 0.71	16.26 ± 0.56	-3.78 ± 2.86	0.008*
PGL	Female	13.82 ± 1.16	14.25 ± 1.91	+2.75 ± 6.57	0.399
PGL	Male	15.56 ± 0.66	16.07 ± 0.66	+4.69 ± 2.56	0.026*

Note. Values presented as mean ± standard deviation. Hb = hemoglobin; HA = High Altitude group; PGL = Pangalengan group. * $p < 0.05$ for paired t-test comparing T0 to T1 within group.

Hematocrit Alterations

Hematocrit levels were expected to show changes similar to those observed in hemoglobin levels, as shown in Table 3. The HA group exhibited significant decrease in both sexes with the female observed to have recorded a 5.42% ± 2.24% reduction from 44.92 ± 1.20% to 42.50 ± 1.81% (paired t-test: $t=-4.978$, $p=0.016$) and the male showed an even larger decline of 6.06% ± 2.68% from 51.79 ± 2.21% to 48.62 ± 1.86% (paired t-test: $t=-6.169$, $p<0.001$). These reductions were statistically significant and clinically important.

A contrasting observation in the PGL group showed stable hematocrit levels throughout this study. The female recorded only a small change of -0.20% ± 7.69% from 44.67 ± 2.69% to 44.62 ± 4.73% ($t=-0.031$, $p=0.978$) and the same trend was observed for the male with +0.22% ± 3.02% from 48.90 ± 2.61% to 48.96 ± 1.85% ($t=0.104$, $p=0.920$). The difference between the male athlete groups was statistically significant ($t = -4.260$, $p < 0.001$), indicating variation in hematological profiles across specific training methods.

Table 3. Hematocrit Changes by Group and Gender

Group	Gender	Hct T0 (%)	Hct T1 (%)	Change (%)	p-value
HA	Female	44.92 ± 1.20	42.50 ± 1.81	-5.42 ± 2.24	0.016*
HA	Male	51.79 ± 2.21	48.62 ± 1.86	-6.06 ± 2.68	<0.001*
PGL	Female	44.67 ± 2.69	44.62 ± 4.73	-0.20 ± 7.69	0.978
PGL	Male	48.90 ± 2.61	48.96 ± 1.85	+0.22 ± 3.02	0.920

Note. Values presented as mean ± standard deviation. Hct = hematocrit; HA = High Altitude group; PGL = Pangalengan group. * $p < 0.05$ for paired t-test comparing T0 to T1 within group.

Individual Response Variability

Individual athletes exhibited considerable variability in hematological adaptations to altitude training as presented in Figure 1. The participants were categorized based on absolute hemoglobin changes using established criteria into positive responders ($\Delta > +0.4$ g/dL), non-responders ($\Delta -0.4$ to $+0.4$ g/dL), and negative responders ($\Delta < -0.4$ g/dL). None of the participants in the HA group ($n=12$) were classified as positive responders (0%), while the majority were negative responders ($n=9$; 75.0%), and only three (25.0%) maintained stable hemoglobin concentrations, leading to categorization as non-responders. This distribution contrasted sharply with the PGL group ($n=11$), where positive responders comprised the majority ($n=7$; 63.6%), non-responders accounted for 27.3% ($n=3$) and only one (9.1%) was a negative responder. The chi-square analysis further showed a statistically significant relationship between the training group and the response category ($\chi^2 = 11.52$, $p = 0.003$). The result suggested a substantial influence of the training regimen on individual response profiles.

Hemoglobin changes across all subjects ranged from -1.6 g/dL to +1.2 g/dL. However, the HA group mostly showed negative shifts, ranging from -1.6 to +0.2 g/dL, whereas the PGL group predominantly showed positive adaptations, ranging from -0.8 to +1.2 g/dL. These substantial inter-individual variations emphasized the need for individualized monitoring and the constraints inherent in drawing population-level inferences regarding responses to altitude training.

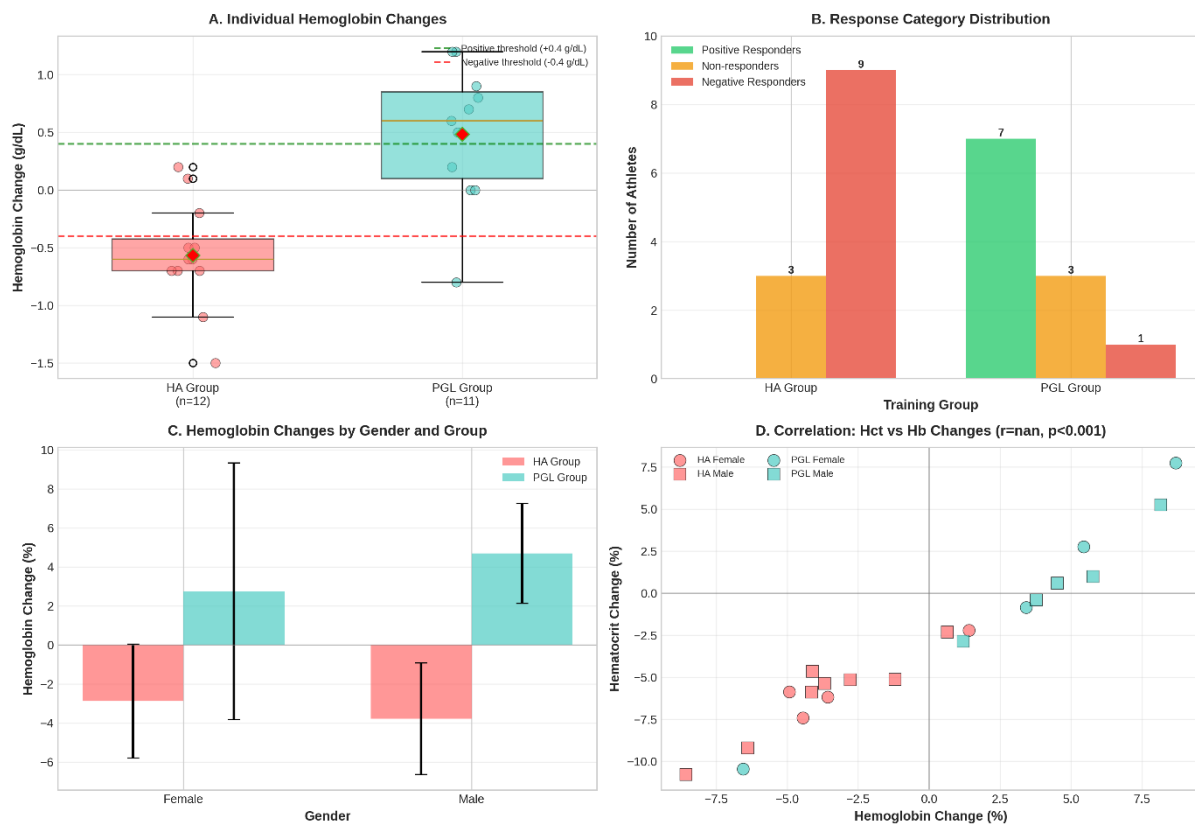


Figure 1. Individual Hematological Responses to Altitude Training

Iron Status and Predictive Relationships

Contrary to the fourth hypothesis, baseline serum ferritin did not significantly predict the magnitude of hemoglobin response (Pearson $r = -0.122$, $p = 0.579$). This non-significant weak negative association persisted in sex-stratified analyses and when percentage changes were substituted for absolute values. Mean baseline ferritin was 68.05 ± 27.90 ng/mL (HA) and 91.85 ± 49.22 ng/mL (PGL). Both groups showed decrements in ferritin at T1 (HA: 57.50 ± 18.35 ng/mL; PGL: 71.20 ± 38.82 ng/mL), suggesting active iron utilization during altitude exposure. However, as ferritin levels in this cohort remained above clinical deficiency thresholds throughout the study, the absence of a predictive relationship may reflect that iron sufficiency, rather than surplus, is the operative constraint, with erythropoietic capacity determined by factors beyond this threshold.

Gender Comparisons

Gender-based analyses showed complex patterns that partially supported the third hypothesis. This was observed because the male and female athletes exhibited similar percentage changes in hemoglobin when the training groups were combined. The males had $-0.52\% \pm 5.03\%$, and the females recorded $-0.07\% \pm 5.59\%$ ($p = 0.851$); similar absolute changes were observed at -0.11 ± 0.76 g/dL and 0.01 ± 0.77 g/dL ($t = -0.357$, $p = 0.724$), respectively. However, these overall statistics masked important differences within each group. The male athletes in the HA group had a larger absolute decrease in hemoglobin (-0.65 ± 0.49 g/dL) than females (-0.40 ± 0.41 g/dL), but the difference was not statistically significant ($p = 0.371$). Conversely, the PGL group showed a larger absolute increase in males ($+0.51 \pm 0.48$ g/dL) than in females ($+0.43 \pm 0.92$ g/dL; $p = 0.871$). The percentage changes followed similar patterns but showed considerable variability within each group. These results suggested that the proportional adaptive response to altitude training could be more strongly influenced by the training program than by sex-specific physiological traits, despite significant gender differences in initial blood parameters.

Discussion

The most striking finding of this study is the opposite hemoglobin trajectory observed between the HA and PGL groups: continuous altitude residence led to significant reductions, whereas intermittent exposure with normoxic recovery produced significant gains, particularly in male athletes. H_1 did not anticipate this divergence and challenges the assumption that any sustained exposure to altitude uniformly stimulates erythropoiesis. The contrast between an 8.47% difference in hemoglobin outcomes and a parallel 66.5% difference in negative responder rates ($\chi^2 = 11.52$, $p = 0.003$) suggests that protocol structure, rather than individual predispositions, is the primary determinant of adaptation direction (Mujika et al., 2024; Skattebo & Hallén, 2022).

These results are broadly consistent with, yet extend, findings from prior studies. Chen et al. (2023), in a systematic meta-analysis primarily drawing on European and North American cohorts, reported that LHTL strategies implemented at approximately 2,500 m for three weeks produced the most robust aerobic improvements (SMD = 0.67 for VO_{2max} ; SMD = 0.50 for hemoglobin). The present study's PGL protocol, which approximates LHTL by incorporating normoxic recovery sessions at lower elevation, aligns with this finding and extends it to an Indonesian elite rowing population that has not previously been represented in such syntheses. Importantly, where Chen et al. (2023) compared LHTL against normoxic training, the current study compares LHTL-analogous against LHTH-analogous protocols at the same altitude and duration, isolating the contribution of normoxic recovery periods more precisely.

Cerda-Kohler et al. (2022) examined Chilean elite rowers using a moderate-altitude LHTH design and reported improved submaximal but not maximal performance (7.3% increase in power at VT1, 6.9% at VT2; no change in VO_{2max}), without significant improvements in hemoglobin. The HA group in the present study followed a comparable LHTH approach and, similarly, failed to elicit a positive hemoglobin response. The parallel across geographically and genetically distinct rowing populations strengthens the inference that continuous residence at high altitude without normoxic recovery may be insufficient or even counterproductive for erythropoietic stimulation, regardless of population background (Villafuerte et al., 2022). This represents a meaningful addition to the rowing-specific altitude literature.

The mechanistic explanation for the HA group's negative hemoglobin trajectory may involve cumulative hypoxic stress exceeding erythropoietic capacity, with in normoxic recovery windows. Nolte et al. (2025) demonstrated that hypoxia-induced erythropoiesis increases iron demand, which competes with immune function, with hepcidin playing a central regulatory role. The observed decline in ferritin in the HA group (from 68.05 to 57.50 ng/mL) is consistent with iron mobilization for erythropoiesis. In contrast, iron supply may have been insufficient to sustain erythropoiesis under continuous hypoxic stress (Koivisto-Mørk et al., 2021). The PGL group's periodic normoxic sessions may have moderated hepcidin suppression and allowed partial iron recovery, enabling net erythropoietic gain. This mechanistic narrative, supported by Nolte et al. (2025) and Neumann et al. (2021), is consistent with the 8.47% performance differential but remains inferential given the absence of EPO and hepcidin measurements in this study.

The absence of a significant ferritin-hemoglobin correlation ($r = -0.122$, $p = 0.579$), which contradicts H_4 , is consistent with findings from Mujika et al. (2025), who similarly found that baseline iron stores did not predict hemoglobin-mass changes in world-class water polo players. This convergence across two independent studies using different sports and populations suggests that, above clinical deficiency thresholds, ferritin is not a reliable predictor of individual adaptation (Koivisto-Mørk et al., 2021; Mujika et al., 2024). Mujika et al. (2025) instead identified sleep quality as a significant predictor ($\beta = 0.51$, $p = 0.04$), underscoring that recovery-related factors may explain more variance in adaptation outcomes than baseline nutritional markers. The current study did not systematically assess sleep or other recovery indicators, which represents both a limitation and a priority for future research.

From a mechanistic standpoint, Carin et al. (2025) reported that post-altitude elevation in hemoglobin mass in elite swimmers was sustained not by continued erythropoiesis but by prolonged erythrocyte survival, with implications for competition scheduling. Whether an analogous mechanism operates in the PGL group in the present study cannot be determined from hemoglobin concentration measurements alone; total hemoglobin mass via the CO-rebreathing method would be required to differentiate between production and survival effects (Cubel et al., 2025). Nevertheless,

the finding that PGL group gains persisted into the T2 recovery phase (9 days post-altitude), as observed in hemoglobin and hematocrit trajectories, is consistent with erythrocyte survival contributing to sustained elevation. Öntürk et al. (2025) further demonstrated complex interactions among HIF-1 α , EPO, hepcidin, and nitric oxide that vary by training modality, providing additional mechanistic context for why aerobic-dominant rowing training may elicit different molecular responses than sports with higher anaerobic components (Jakovac & Belamárić, 2025).

The sex-based findings partially supported H₃: while males showed greater absolute changes in both directions (larger decrements in HA, larger increments in PGL), proportional changes did not differ significantly by sex when training groups were considered separately. This is consistent with the proposition that baseline erythropoietic potential confers an absolute, but not necessarily proportional, advantage, and aligns with the observation by Mujika et al. (2025) that sex-specific factors, such as menstrual phase, modulate responses more through cycle-specific variation than through persistent sex differences in adaptation direction (Baar et al., 2022). However, statistical power for sex-stratified comparisons in the present study was insufficient (n = 4 females per group), and these findings should be regarded as preliminary rather than conclusive.

From a practical standpoint, the eight-fold reduction in negative responder rate (from 75% in HA to 9.1% in PGL, $\chi^2 = 11.52$, $p = 0.003$) has direct implications for program design. If this differential is replicable, the protocol structure, specifically the incorporation of normoxic recovery sessions, may be a more effective lever for minimizing non-response than screening based on ferritin or other baseline biomarkers. For Indonesian national rowing programs operating with limited access to purpose-built hypoxic facilities, the PGL protocol demonstrates that strategically deploying natural-elevation geography alongside lowland training sites can produce favorable hematological outcomes. This supports the broader argument for geographically adaptive, evidence-based protocols in regions where altitude-training infrastructure is constrained (Wilber, 2022; Marzorati, 2020).

Research Contribution

This study provides the first systematically collected hematological dataset from Indonesian national-team rowers across a full altitude training camp, addressing the geographic evidence gap identified by Sitkowski (2023) and Villafuerte (2022). The direct protocol comparison (HA vs. PGL) at identical altitude and duration offers a level of methodological control not available in prior observational studies, where protocol differences were typically confounded with altitude or duration differences. The eight-fold reduction in negative responders attributable to protocol structure rather than individual genetics contributes to the growing literature challenging the genetic determinism implicit in the "responder vs. non-responder" framework. The convergence of PGL outcomes with LHTL predictions from European and North American meta-analyses in a Southeast Asian population strengthens the generalizability of LHTL principles across diverse genetic backgrounds, underscoring the importance of locally adapted implementation.

Limitations

The sample size (N=23) constrained statistical power, particularly for sex-specific analyses (n=4 females per group), and this raised the possibility of specific comparisons (female HA hemoglobin: $p=0.145$) leading to Type II errors rather than authentic null effects. Evaluating hemoglobin concentration rather than total hemoglobin mass, as required by the gold-standard CO-rebreathing method, could also yield confounding results due to variations in plasma volume. However, the simultaneous fluctuations in hematocrit indicated genuine changes in red blood cell counts. The lack of mechanistic biomarkers such as EPO, HIF-1 α , hepcidin, RET-HE, and senescence constrained physiological interpretation. The nine-day follow-up period also hindered the evaluation of adaptation persistence and optimal competition timing, which Wilber (2022) emphasized as critical practical considerations.

Furthermore, the absence of performance tests critically obstructed efforts to evaluate the ability of hematological enhancements to provide competitive advantages, as those who identified non-hematological performance mechanisms did. The quasi-experimental design, with non-randomized group assignment, introduced potential confounding variables from unmeasured factors such as sleep quality, stress, and nutrition. Mujika et al. (2025) recognized sleep as a predictor of

adaptations, but this study did not systematically evaluate recovery indicators. The homogeneity of the Indonesian elite rowers also limited generalizability across different ages, sports, genetic backgrounds, and training statuses. However, the specificity constituted a strength for the underrepresented group.

Suggestions

Future investigations should address the mechanistic and temporal gaps identified here. Comprehensive biomarker panels including EPO, HIF-1 α , hepcidin, RET-HE, and markers of erythrocyte senescence are needed to elucidate the competing contributions of production versus survival to hemoglobin mass changes. Total hemoglobin mass measurement via CO-rebreathing should replace concentration-based measures to eliminate plasma-volume confounding. Follow-up periods should extend for at least 4 weeks post-altitude to characterize adaptation-decay kinetics and inform competition scheduling. Performance testing (VO₂max, threshold power, on-water time trials) at each measurement point would enable the determination of whether hematological improvements translate into competitive advantage, given evidence that non-hematological mechanisms also contribute to post-altitude performance gains. Systematic assessment of recovery indicators (sleep, heart rate variability, nutritional intake) is essential, given the evidence that sleep quality may be a stronger predictor of adaptation than baseline iron status. Finally, expanding to larger, more sex-balanced samples, adolescent athletes, and comparative Southeast Asian populations would improve both statistical power and regional generalizability.

CONCLUSION

This study demonstrates that the design of the altitude training protocol, specifically the inclusion of normoxic recovery periods, is a stronger determinant of hematological adaptation than altitude exposure per se, baseline iron stores, or sex-specific physiology in Indonesian elite rowers. The intermittent PGL protocol produced significant hemoglobin gains (+4.69% in males, $p=0.026$). In comparison, continuous HA exposure led to unexpected reductions (-3.78% in males, $p = 0.008$), yielding an 8.47% differential and a striking 66.5% difference in negative responder rates ($\chi^2 = 11.52$, $p = 0.003$). Baseline ferritin did not predict hemoglobin response magnitude ($r = -0.122$, $p = 0.579$), suggesting that iron sufficiency above deficiency thresholds is necessary but not sufficient for erythropoietic adaptation. These findings extend LHTL principles to an underrepresented Southeast Asian elite population and support the proposition that recovery structure within altitude camps drives adaptation direction more than individual genetic predisposition. Practitioners designing altitude training programs for Indonesian national rowing teams should prioritize intermittent exposure protocols with planned normoxic recovery periods over continuous high-altitude residence. Future research should integrate mechanistic biomarkers, total hemoglobin mass measurement, performance testing, and extended follow-up to validate these findings and establish individualized, precision-guided altitude training protocols for elite endurance athletes.

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AUTHOR CONTRIBUTION STATEMENT

In our manuscript, DRN, AMS, PP, HA, GAS, BS, and DDC contributed: DRN conceptualized the study, designed the methodology, analyzed the results, and coordinated data collection. AMS and PP contributed to the manuscript review. HA and GAS contributed to the data collection. BS and DDC performed data analysis and interpreted the results.

AI DISCLOSURE STATEMENT

The author used the digital language tool QuillBot in preparing the manuscript to enhance clarity and readability while preparing the manuscript. All contents are meticulously reviewed and edited by the author, who is solely accountable for the accuracy and integrity of this study.

CONFLICTS OF INTEREST

The authors confirm that there are no conflicts of interest that can influence the conduct of this study, the analysis of data, the preparation of the manuscript, or the publication.

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