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Blood Pressure Levels and Prevalence of Hypertension in Relation to Altitude and Ethnicity Among an Occupational Health Screening Population on the Qinghai–Tibetan Plateau

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Blood Pressure Levels and Prevalence of Hypertension in Relation to Altitude and Ethnicity Among an Occupational Health Screening Population on the Qinghai–Tibetan Plateau

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Hongguang Fan: Conceptualization, Supervision, Writing – review & editing, Funding acquisition

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Blood Pressure Levels and Prevalence of Hypertension in Relation to Altitude and Ethnicity Among Health check-up Population on the Qinghai–Tibetan Plateau

Abstract

Objective: To investigate blood pressure levels and hypertension prevalence across altitudes and ethnic groups in an occupational health screening population on the Qinghai–Tibetan Plateau, and to analyze the independent and interactive effects of altitude and ethnicity on blood pressure and hypertension.

Methods: A total of 6,548 participants were enrolled. Data on demographics, altitude, ethnicity, blood pressure, age, sex, BMI, dyslipidemia, and dysglycemia were collected. Statistical analyses included t-tests, ANOVA, chi-square tests, ANCOVA, and binary logistic regression, with stratified analyses by ethnicity.

Results: The overall hypertension prevalence was 20.7% (1,357/6,548): 25.3% in Han, 16.4% in Tibetans, and 23.9% in other ethnic groups ($\chi^2 = 48.362$, $P < 0.001$). Prevalence in low- (1,500–2,500 m), moderate- (2,500–3,500 m), and high-altitude (3,500–4,500 m) groups was 28.8%, 15.9%, and 17.6%, respectively ($\chi^2 = 78.521$, $P < 0.001$). ANCOVA showed that both altitude and ethnicity had independent main effects on systolic and diastolic blood pressure (all $P < 0.05$), with significant interactions (SBP: $F = 2.865$, $P = 0.022$; DBP: $F = 6.310$, $P < 0.001$). The Han–Tibetan blood pressure difference was largest at 2,500–3,500 m. Logistic regression identified altitude as an independent protective factor ($P < 0.001$), with ORs of 0.417 (95% CI: 0.329–0.530) for moderate altitude and 0.695 (95% CI: 0.550–0.876) for high altitude. Ethnicity main effect and altitude × ethnicity interaction were not significant in the full model. Stratified analyses showed that Tibetans had stronger protective effects at moderate and high altitudes than Han (all $P < 0.001$).

Conclusions: In this occupational health screening population, blood pressure and hypertension prevalence show significant altitudinal and ethnic disparities, with a significant altitude–ethnicity interaction. Tibetans demonstrate the most pronounced blood pressure advantage and hypertension protection at moderate altitudes. Hypertension prevalence is primarily influenced by altitude and traditional risk factors, while ethnic differences largely reflect physiological adaptive characteristics.

Keywords: Qinghai–Tibetan Plateau; altitude; ethnicity; blood pressure; hypertension; interaction

1. Introduction

Hypertension is a highly prevalent cardiovascular risk factor and a leading cause of disability and mortality worldwide, with complications including stroke and myocardial infarction posing a serious threat to population health [1]. Although its precise mechanisms remain incompletely understood, genetic predisposition, metabolic disorders, obesity, aging, and lifestyle factors are all implicated in its pathogenesis. Elucidating the epidemiological characteristics and risk factors of hypertension in specific high-risk regions is therefore critical for developing targeted prevention strategies.

The hypoxic environment at high altitudes may disrupt blood pressure regulation. Hypertension prevalence ranges from 8.6% to 55.9% [2] and varies with altitude and community [3–6]. Populations above 2,500 m experience chronic sustained hypobaric hypoxia, distinct from acute exposure. However, findings on the association between hypertension and altitude remain inconsistent. Some studies report decreasing blood pressure with rising elevation on the Qinghai–Tibetan Plateau [7–9]. In contrast, a retrospective study of 16,913 Tibetans above 3,000 m found that hypertension prevalence increased by ~2% per 100 m altitude gain [10], and Aryal et al. [6] reported a rise of 17/9.5 mmHg per 1,000 m. A Peruvian study observed no significant association [11], while a Tibetan study revealed a U-shaped relationship, with prevalence lowest at ~3,800 m [12]. A study in China's Ganzi region identified altitude ⩾3,500 m and alcohol consumption as independent risk factors [13]. Overall, existing evidence remains conflicting across populations and settings.

Qinghai Province, in the northeastern Qinghai–Tibetan Plateau, covers >722,300 km^2 with elevations from 1,644 to 6,861 m; human settlements are mostly below 4,500 m. Its 39 county-level units encompass diverse environments, with Han and Tibetan populations being the most numerous among several ethnic groups. Ethnic differences may affect disease manifestation—for example, hypertension prevalence among Himalayan Tibetans (41%) significantly exceeds that in local non-Tibetans (18%) [14]. This multi-ethnic distribution across a broad altitudinal gradient provides an ideal setting to investigate ethnicity–altitude interactions in hypertension.

Beyond altitude, hypertension prevalence varies across ethnic groups due to lifestyle and dietary differences [2,3]. Yet most studies have examined altitude or ethnicity in isolation, lacking systematic exploration of their combined effects—a gap that hinders interpretation of observed prevalence differences across groups and altitudes. Moreover, treating blood pressure solely as binary overlooks quantitative information in continuous values. This study therefore utilized health screening data (2014–2019) from employees of government agencies and public institutions in Qinghai Province to investigate the effects of altitude and ethnicity on hypertension and their interaction in high-altitude areas. Given the scarcity of community-level studies simultaneously considering both factors on the Qinghai–Tibetan Plateau, we also aimed to determine hypertension prevalence and identify associated risk factors, adopting a dual perspective—continuous blood pressure and binary hypertension status—to comprehensively elucidate underlying mechanisms. The findings may inform altitude- and ethnicity-specific precision prevention strategies, reducing the disease burden of hypertension in high-altitude regions. It should be noted that our study population predominantly comprises individuals with higher education and stable occupations, warranting caution when extrapolating results to the general highland population.

2. Methods

2.1 Data Source and Study Population

A regular health check-up program was conducted by the Qinghai Cardio-Cerebrovascular Specialty Hospital in the following areas of Qinghai Province between 2014 and 2019: Jiegu Town (3,681 m), Zhiduo County (4,188 m), Qumalai County (4,226 m), and Chendu County (3,831 m) in

Yushu Tibetan Autonomous Prefecture; Maduo County (4,200 m), Jiuzhi County (3,626 m), Dari County (4,001 m), Maqin County (3,700 m), Banma County (3,970 m), and Gande County (4,050 m) in Guoluo Tibetan Autonomous Prefecture; Dulan County (3,180 m) in Haixi Mongolian and Tibetan Autonomous Prefecture; Tianjun County (3,406 m) in Haibei Tibetan Autonomous Prefecture; Zeku County (3,655 m) in Huangnan Tibetan Autonomous Prefecture; and Xining City and its suburban areas (2,260 m). Data were extracted from routine health examination reports of 8,888 participants, all of whom belonged to various ethnic groups and had resided in the sampling locations for more than three years.

Inclusion criteria: (1) age $\geqslant$ 18 years; (2) continuous residence in the study area for $\geqslant$ 3 years; (3) completion of questionnaire survey, physical examination, and blood pressure measurement.

Exclusion criteria: (1) secondary hypertension (e.g., renal hypertension, endocrine hypertension); (2) acute phase of severe cardiovascular or cerebrovascular diseases (e.g., acute myocardial infarction, cerebral hemorrhage); (3) malignancy; (4) cognitive impairment or psychiatric disorders; (5) incomplete clinical data; (6) inability to complete the health screening questionnaire due to language barriers.

After applying the above exclusion criteria, 6,548 individuals (73.67%) were included in the final analysis (see Figure 1 for the exclusion flow diagram). Among the 6,548 participants, 3,067 were Han, 3,410 were Tibetan, and 71 belonged to other ethnic groups; 2,110 were in the low-altitude group (1,500 – 2,500 m), 2,023 in the moderate-altitude group (2,500 – 3,500 m), and 2,415 in the high-altitude group (3,500 – 4,500 m).

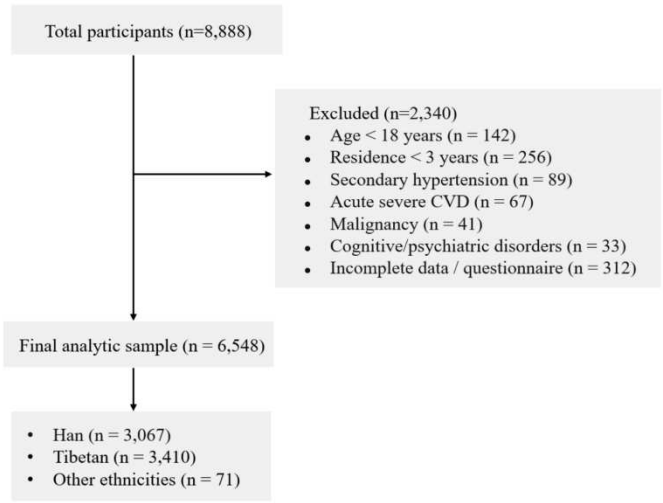


Figure 1. Flow diagram of participant selection. A total of 8,888 individuals underwent regular health check-ups; 6,548 were included in the final analysis after applying exclusion criteria.

To assess selection bias, baseline characteristics between included and excluded participants were compared: age (45.2 $\pm$ 12.3 vs. 44.8 $\pm$ 11.9 years, t = 1.26, P = 0.207), sex distribution

(male proportion: 49.1% vs. 48.7%, χ^2 = 0.18, P = 0.672), and ethnic distribution (Tibetan proportion: 38.5% vs. 37.9%, χ^2 = 0.31, P = 0.577) showed no statistically significant differences, indicating that the exclusion process did not substantially alter the representativeness of the study population.

Data collection was conducted annually from May to October, with yearly sample proportions as follows: 2014 (15.73%), 2015 (17.19%), 2016 (16.08%), 2017 (16.42%), 2018 (16.85%), and 2019 (17.73%).

This was a retrospective study based on health examination records and was approved by the Medical Ethics Committee of Qinghai Cardio-Cerebrovascular Specialty Hospital, which waived the requirement for informed consent.

2.2 Diagnostic Criteria and Data Collection

2.2.1 Outcome Variable Definition

The outcome variable was "hypertension," analyzed from two perspectives: as continuous and as binary data.

(1) Continuous form: Systolic blood pressure (SBP) and diastolic blood pressure (DBP) as continuous variables (measured to the nearest 1 mmHg). Blood pressure was measured using an Omron HEM-7136 electronic sphygmomanometer, strictly following the standardized procedures outlined in the *Chinese Guidelines for Blood Pressure Measurement*.

(2) Binary form: Hypertension (yes/no). Diagnosis was based on the *Chinese Guidelines for the Prevention and Treatment of Hypertension (2024 Revision)*, defining hypertension as SBP $\geqslant$ 140 mmHg and/or DBP $\geqslant$ 90 mmHg [15].

2.2.2 Exposure Variable, Modifier, and Covariates

2.2.2.1 Core Exposure Variable: Altitude

Since the study participants (predominantly employees of government agencies and public institutions) generally resided and worked in county seat areas, and the elevation differences among county-level administrative centers in Qinghai Province were generally within $\pm$100 m, altitude was assigned based on the elevation of the local county government seat. A pre-survey of 500 randomly selected participants confirmed that 92.3% resided within 5 km of the county seat, with an elevation difference between actual residence and county seat of 23.6 $\pm$ 18.9 m (range: 0–89 m). This finding supports the rationale for using county seat elevation as a grouping basis, although it cannot completely eliminate misclassification bias.

Based on the elevation of the workplace, participants were divided into three groups:

low-altitude group: 1,680–2,499 m (reference group, coded as 0); moderate-altitude group: 2,500–3,499 m (coded as 1); high-altitude group: ≥ 3,500 m (coded as 2). It should be noted that this classification method does not use the actual residential altitude of participants, which may introduce non-differential misclassification. For example, some participants residing in low-altitude townships (e.g., 2,400 m) around the county seat may be classified into the moderate-altitude group (2,500–3,499 m); conversely, participants residing in high-altitude pastoral areas (e.g., 3,500 m) but whose county seat is at 3,490 m may also be classified into the moderate-altitude group. Such misclassification typically attenuates the true association between altitude and hypertension towards the null, potentially underestimating the protective effect of altitude or overestimating its risk. Therefore, the observed association between altitude and hypertension in this study should be considered a conservative estimate.

Altitude data were validated using Google Maps (https://www.google.com/maps). The 2,500 m cut-off was based on the international criteria for chronic mountain sickness—the Qinghai standard [16]. This classification enables the analysis of the effects of residential altitude (more specifically, the altitude at which participants reside and work) on the development of hypertension.

2.2.2.2 Modifier: Ethnicity

The ethnic composition of the study population included Han, Tibetan, and other ethnic groups (such as Hui, Tu, and Mongolian). Ethnicity was determined based on identification documents. Participants were categorized into three groups: Han (coded as 1), Tibetan (coded as 2), and other ethnicities (coded as 3).

The interaction term altitude × ethnicity was included to test their combined effect on hypertension.

2.2.2.3 Covariates

Based on previous hypertension-related studies, the following variables were included as covariates:

(1) Demographic factors:** Sex (male = 0, female = 1); age (continuous variable, or categorized as 18–25, 26–34, 35–44, 45–54, 55–64, ≥ 65 years); educational level (primary school or below / secondary school / college or above).

(2) Clinical and genetic factors:** Body mass index (BMI; continuous variable, kg/m^2), calculated as weight in kilograms divided by height in meters squared (BMI = weight/$height^2$); dyslipidemia (yes/no); dysglycemia (yes/no). All these items were documented in the health examination reports.

2.2.3 Data Collection Methods

Trained investigators used standardized questionnaires to collect basic participant information (age, sex, ethnicity, workplace altitude). Anthropometric measurements including height and weight were obtained: height was measured barefoot to the nearest 0.1 cm, and weight was measured in a fasting state with light clothing to the nearest 0.1 kg, from which BMI was calculated. Blood pressure was measured using an Omron HEM-7136 electronic sphygmomanometer, with three measurements taken at 5-minute intervals, and the average value was used for analysis. Fasting venous blood samples were sent to the laboratory of each examination center, where fasting blood glucose and other biochemical parameters were measured using an automatic biochemical analyzer (Hitachi 7600-020).

All data were double-entered into an EpiData 3.1 database (EpiData Association). After data entry, 10% of the records were randomly selected for verification to ensure that the data entry error rate was < 0.5%.

2.3 Quality Control

Blood pressure measurement equipment:** All electronic sphygmomanometers used in the examination centers were calibrated by a third-party institution prior to the study to ensure consistent measurement accuracy. Measurement parameters were uniformly configured in accordance with the requirements of the *Chinese Guidelines for Blood Pressure Measurement*.

Personnel training:** Investigators and examination staff were required to hold relevant professional certifications and possess at least three years of relevant work experience. Prior to the study, all staff participated in a three-day specialized training program covering hypertension diagnostic criteria, standardized blood pressure measurement procedures, questionnaire administration, and data entry. Only those who passed the assessment (theoretical score $\geqslant$ 80% and practical diagnostic concordance rate $\geqslant$ 95%) were permitted to participate in the study.

2.4 Statistical Analysis

Statistical analyses were performed using SPSS version 26.0, with a significance level set at $\alpha = 0.05$. A total of 6,548 participants were included in this large-scale epidemiological survey, ensuring adequate representativeness and statistical power. Continuous variables were expressed as mean $\pm$ standard deviation (Mean $\pm$ SD), and categorical variables as frequencies (percentages, %).

Baseline characteristics were compared between groups using t-tests (for two groups) or one-way ANOVA (for multiple groups) for continuous variables, and chi-square tests for categorical variables, to assess the balance of baseline covariates across altitude and ethnicity groups, thereby minimizing confounding effects.

One-way analysis of covariance (ANCOVA) was used to compare SBP and DBP across altitude and ethnicity groups, adjusting for covariates including age group, sex, BMI, dyslipidemia, and dysglycemia. Preliminary assumption testing confirmed that the dependent variables (SBP and

DBP) were approximately normally distributed across groups (Shapiro–Wilk test $P > 0.05$, approximating normality due to large sample size), and Levene's test for homogeneity of variances was non-significant ($P > 0.05$), satisfying the homogeneity of variance assumption. The altitude × ethnicity interaction term was included in the model to evaluate their synergistic effect on blood pressure levels, using Type III sums of squares to calculate F-values and P-values. Estimated marginal means (EM means) were used to describe blood pressure levels for each altitude–ethnicity subgroup, illustrating the specific pattern of the interaction.

2.4.1 Multicollinearity Analysis

Given the inclusion of multiple independent variables in the models (altitude, ethnicity, age group, BMI, dyslipidemia, etc.), variance inflation factor (VIF) was calculated for all predictors in both the logistic regression and ANCOVA models to avoid distortion from multicollinearity. The criteria for multicollinearity were: $VIF < 10$, no significant multicollinearity; $10 \leqslant VIF < 100$, moderate multicollinearity; $VIF \geqslant 100$, severe multicollinearity. If moderate or higher multicollinearity was detected, variables with high intercorrelation were removed or combined to ensure model stability.

2.4.2 Sensitivity Analysis

To test the robustness of the findings, sensitivity analyses were conducted using two approaches: (1) excluding the "other ethnicities" group (n = 71) and re-running the ANCOVA and logistic regression analyses in the Han and Tibetan populations only; (2) adjusting the exclusion criteria for extreme blood pressure values (SBP > 220 mmHg or DBP > 130 mmHg) and re-analyzing the data. If the results from both approaches showed no substantial differences from the primary analyses (consistent trends in ORs, F-values, and P-values), the findings were considered robust and reliable.

3. Results

3.1 Baseline Characteristics and Hypertension Prevalence

A total of 6,548 participants were included in this survey, comprising 4,191 males (64.0%) and 2,357 females (36.0%), with an age range of 18–75 years and a mean age of 42.08 ± 12.67 years. Significant differences in baseline characteristics were observed across altitude groups, with statistically significant differences in age, sex, BMI, dyslipidemia, dysglycemia, and hemoglobin abnormalities (all $P < 0.05$). Detailed baseline characteristics are presented in Table 1.

Table 1. Baseline characteristics of participants by altitude group

Characteristic	Low altitude (1,500 – 2,500 m) n = 2,114	Moderate altitude (2,500 – 3,500 m) n = 2,026	High altitude (3,500 – 4,500 m) n = 2,416	Statistic	P-value
Age (years), Mean ± SD |	44.28±14.03	42.75±12.08	39.59±11.41	F=83.514	<0.001
Sex, n (%)				χ^2=42.996	<0.001
Male	1255(59.5)	1276(63.1)	1660(68.7)		
Female	855(40.5)	747(36.9)	755(31.3)		
BMI (kg/m^2), Mean ± SD	23.34±3.56	25.04±3.89	24.52±3.70	F=114.389	<0.001
Dyslipidemia, n (%)	829(39.3)	863(42.7)	773(32.0)	χ^2=56.788	<0.001
Dysglycemia, n (%) |	129(6.1)	137(6.8)	100(4.1)	χ^2=16.065	<0.001
Hemoglobin abnormality, n (%)				χ^2=612.447	<0.001
Normal	1979(93.9)	1309(68.6)	1096(62.1)		
Abnormal	125(5.9)	590(30.9)	659(37.3)		
Ethnicity, n (%)				χ^2≈378.0*	<0.001
Han	1853(87.7)	597(29.5)	622(25.7)		
Tibetan	195(9.2)	1428(70.5)	1790(74.1)		
|Other	66(3.1)	1(0.05)	4(0.2)		

Note:Age and BMI were compared using one-way ANOVA (F-values); sex, dyslipidemia, dysglycemia, hemoglobin abnormality, and ethnicity were compared using chi-square tests (χ^2 values). Hemoglobin abnormality was used for baseline description only and was not included in multivariable adjustment models. Missing rates for all variables were < 5% (except hemoglobin abnormality), and complete-case analysis was applied.

* The χ^2 value for ethnicity was estimated from the cross-tabulation data.

Blood pressure levels differed significantly across altitude groups. In the low-altitude group (1,500–2,500 m), SBP was 125.81 ± 18.98 mmHg and DBP was 80.92 ± 12.01 mmHg; in the moderate-altitude group (2,500–3,500 m), SBP was 116.62 ± 18.23 mmHg and DBP was 74.94 ± 13.12 mmHg; in the high-altitude group (3,500–4,500 m), SBP was 119.78 ± 16.67 mmHg and DBP was 80.47 ± 13.21 mmHg. One-way ANOVA revealed significant differences among the three groups for both SBP (F = 141.316, P < 0.001) and DBP (F = 141.009, P < 0.001). Post-hoc pairwise comparisons using the LSD test showed that for SBP, the low-altitude group had significantly higher values than both the moderate- and high-altitude groups, and the high-altitude group had significantly higher values than the moderate-altitude group (all P < 0.001). For DBP, the low-altitude group had significantly higher values than the moderate-altitude group (P < 0.001), and the high-altitude group also had significantly higher values than the moderate-altitude group (P < 0.001), but the difference between the low- and high-altitude groups was not statistically significant (P = 0.234).
The overall prevalence of hypertension was 20.7% (1,357/6,548). By ethnicity, the prevalence was 25.3% (779/3,072) among Han, 16.4% (559/3,413) among Tibetans, and 23.9% (17/71) among other ethnic groups, with statistically significant inter-ethnic differences (χ^2 = 48.362, P < 0.001). By altitude, the prevalence was 28.8% (609/2,114) in the low-altitude group, 15.9% (322/2,026) in the moderate-altitude group, and 17.6% (426/2,416) in the high-altitude group, with significant between-group differences (χ^2 = 78.521, P < 0.001). When grouped by duration of residence, hypertension prevalence was 23.5%, 20.1%, and 18.9% for 1–5 years, 5–10 years, and ≥ 10 years, respectively, with a statistically significant difference (χ^2 = 12.654, P = 0.002).
Baseline characteristic balance analysis revealed that the educational background and income levels of the participants were relatively stable: 78.6% of participants held a college degree or above (77.8% in the high-altitude group, 78.9% in the moderate-altitude group, and 79.1% in the low-altitude group), while 21.4% had a high school education or below (22.2%, 21.0%, and 20.9% in the three groups, respectively), with no statistically significant differences in educational background across altitude groups (P > 0.05). Monthly income also showed no significant differences across altitude groups (P > 0.05).

3.2 Main Effects and Interaction of Altitude and Ethnicity on Blood Pressure Levels

Unadjusted blood pressure levels for each altitude–ethnicity subgroup are presented in Table 2. The results showed that in the low-altitude group, SBP and DBP levels were similar between Han and Tibetan participants; in the moderate-altitude group, SBP and DBP were significantly lower in Tibetans than in Han; and in the high-altitude group, blood pressure increased in both groups,

and the difference between the two narrowed compared with the moderate-altitude group.

Table 2. Systolic and diastolic blood pressure by altitude and ethnicity subgroup (unadjusted)

Ethnicity	Altitude group (m)	SBP (mmHg), Mean ± SD	DBP (mmHg), Mean ± SD
Han	1500-2500	132.5±14.8	82.3±10.2
	2500-3500	128.6±13.7	79.5±9.8
	3500-4500	130.2±14.2	80.8±10.0
Tibetan	1500-2500	131.8±14.5	81.9±10.1
	2500-3500	122.3±13.1	75.6±9.2
	3500-4500	125.7±13.5	77.9±9.5

Note: Other ethnic groups were not listed separately due to small sample size (n = 71). Data are unadjusted raw means ± SD.

After adjusting for age group, sex, BMI, dyslipidemia, and dysglycemia, ANCOVA revealed that both altitude and ethnicity had independent main effects on SBP and DBP (all $P < 0.05$). The altitude × ethnicity interaction was significant for both SBP ($F = 2.865$, $P = 0.022$) and DBP ($F = 6.310$, $P < 0.001$). The results are presented in Table 3.

Table 3. Main effects and interaction of altitude and ethnicity on blood pressure

Factor	SBP		DBP	
	F-value	P-value	F-value	P-value
Altitude	6.722	0.001	2.962	0.052
Ethnicity	4.707	0.009	7.964	<0.001
Altitude × Ethnicity	2.865	0.022	6.310	<0.001
Adjusted R^2	—	0.206	—	0.126

Note: Adjusted for age group, sex, BMI, dyslipidemia (yes = 1, no = 0), and dysglycemia (yes = 1, no = 0). Type III sums of squares were used. Levene's test for homogeneity of variances was non-significant for both SBP and DBP (P > 0.05).

Estimated marginal means analysis showed that the interaction followed a specific pattern: at 1,500–2,500 m, SBP and DBP levels were similar between Han and Tibetan groups, with no statistically significant difference; at 2,500–3,500 m, SBP and DBP were significantly lower in Tibetans than in Han, with the ethnic difference reaching its maximum; and at 3,500–4,500 m, blood pressure levels in both groups converged again, with the difference markedly reduced.

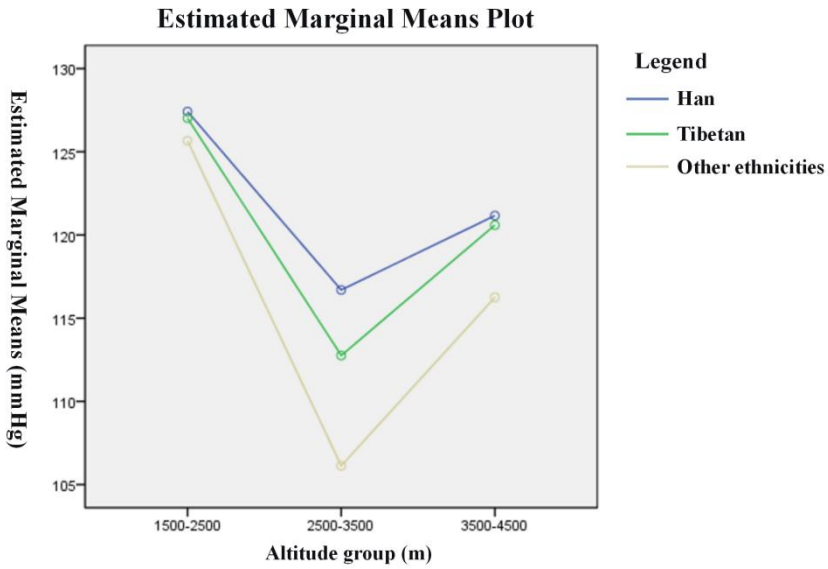


Figure 2. Estimated marginal means of systolic and diastolic blood pressure by altitude and ethnicity group. Adjusted for age group, sex, BMI, dyslipidemia, and dysglycemia. Covariates appearing in the model are evaluated at the following values: age group = 3.49, sex = 1.36, BMI = 24.30, dyslipidemia = 0.38, dysglycemia = 0.06, hemoglobin abnormality = 0.02.

3.3 Logistic Regression Analysis of Hypertension

3.3.1 Full-Population Logistic Regression

Altitude, ethnicity, the altitude × ethnicity interaction term, and covariates (age group, sex, BMI, dyslipidemia, dysglycemia) were simultaneously entered into the binary logistic regression model. The results showed that altitude was an independent protective factor against hypertension (P < 0.001). Compared with the low-altitude group (1,500–2,500 m), the moderate-altitude group (2,500–3,500 m) had significantly reduced hypertension risk (OR = 0.417, 95% CI: 0.329–0.530, P < 0.001), and the high-altitude group (3,500–4,500 m) also had significantly reduced risk (OR = 0.695, 95% CI: 0.550–0.876, P = 0.002). The main effect of ethnicity was not statistically significant (χ^2 = 0.292, P = 0.864), and the overall altitude ×

ethnicity interaction was not statistically significant (χ^2 = 6.481, P = 0.166). In addition, age group (OR = 1.358, 95% CI: 1.293 – 1.426, P < 0.001), BMI (OR = 1.126, 95% CI: 1.106 – 1.147, P < 0.001), and dysglycemia (OR = 1.694, 95% CI: 1.337 – 2.146, P < 0.001) were independent risk factors for hypertension. Detailed results are presented in Table 4.

Table 4. Binary logistic regression analysis of factors associated with hypertension

Variable	B	S.E.	Wald	P-value	OR	95% CI
Constant	-4.673	0.256	334.302	<0.001	0.009	—
Age group	0.306	0.025	151.613	<0.001	1.358	1.293-1.426
Sex (male = 1, female = 0)	-0.118	0.070	2.899	0.089	0.888	0.775-1.018
BMI	0.119	0.009	169.669	<0.001	1.126	1.106-1.147
Dyslipidemia (yes = 1, no = 0)	-0.051	0.067	0.575	0.448	0.950	0.832-1.084
Dysglycemia (yes = 1, no = 0)	0.527	0.121	19.018	<0.001	1.694	1.337-2.146
Altitude (reference: 1,500 – 2,500 m)			54.558	<0.001		
2500-3500m	-0.874	0.122	51.219	<0.001	0.417	0.329-0.530
3500-4500m	-0.364	0.119	9.434	0.002	0.695	0.550-0.876
Ethnicity (reference: Han)			0.292	0.864		
Tibetan	-0.024	0.174	0.019	0.890	0.976	0.693-1.374
Other	-0.158	0.299	0.280	0.597	0.854	0.475-1.534
Altitude × Ethnicity			6.481	0.166		

Note: Model fit: −2 log likelihood = 6046.796, Nagelkerke R^2 = 0.143. Hosmer – Lemeshow goodness-of-fit test: χ^2 = 8.354, df = 8, P = 0.399, indicating good model fit (P > 0.05 indicates

no significant difference between predicted and observed values). ORs and 95% CIs for individual interaction terms (e.g., 2,500–3,500 m × other ethnicity) were not calculable due to small sample sizes and are therefore not shown.

3.3.2 Stratified Logistic Regression by Han and Tibetan Ethnicity

Because the overall altitude × ethnicity interaction was not significant in the full population and the sample size of other ethnicities was small, further stratified logistic regression analyses were performed separately for Han and Tibetan populations, adjusting for age group, sex, BMI, dyslipidemia, and dysglycemia. In a subgroup model including only Han and Tibetan participants, the altitude × ethnicity interaction was re-examined; the likelihood ratio test showed that inclusion of the interaction term did not significantly improve model fit (χ^2 = 3.621, df = 2, P = 0.164), consistent with the non-significant overall interaction in the full population. The stratified regression results showed that in both Han and Tibetan populations, higher altitude was associated with reduced hypertension risk, with Tibetans exhibiting more pronounced protective effects at moderate and high altitudes (all P < 0.001), as detailed in Table 5.

Table 5. Stratified logistic regression analysis of altitude and hypertension in Han and Tibetan populations

Ethnicity	Altitude group (m)	OR	95% CI	P-value
Han	1,500–2,500 (reference)	1.00	—	—
	2,500–3,500	0.389	0.303–0.499	< 0.001
	3,500–4,500	0.681	0.535–0.866	0.002
Tibetan	1,500–2,500 (reference)	1.00	—	—
	2,500–3,500	0.262	0.194–0.354	< 0.001
	3,500–4,500	0.437	0.331–0.577	< 0.001

In both ethnic groups, moderate and high altitudes were protective factors against hypertension. The protective effect was strongest in Tibetans at moderate altitude (2,500–3,500 m) (OR = 0.262), which was significantly lower than that in Han at the same altitude, suggesting that Tibetans have more prominent cardiovascular adaptation to hypobaric hypoxia, with the most pronounced blood pressure regulation advantage at moderate altitudes. Although the interaction term did not reach statistical significance, the stratified analysis revealed a clear trend of between-ethnic differences in ORs (with Tibetans showing stronger protective effects at all altitudes than Han). This trend may provide clues for future mechanistic studies, although cautious interpretation of stratified comparisons is warranted.

3.4 Multicollinearity Diagnostics

Multicollinearity diagnostics were performed for all independent variables in the ANCOVA and logistic regression models, including age, ethnicity, altitude, BMI, total cholesterol, glucose, and

hemoglobin. The results showed that tolerance values ranged from 0.684 to 0.957, and VIF values ranged from 1.045 to 1.462, all far below 10, indicating no significant multicollinearity among the variables. The model structure was stable, and parameter estimates were reliable.

3.5 Sensitivity Analysis

To test the robustness of the primary findings, the following sensitivity analyses were conducted:

Exclusion of other ethnicities:After excluding the small sample of other ethnicities (n = 71) and re-analyzing the altitude × ethnicity interaction on blood pressure and hypertension risk in the Han and Tibetan populations only, the results were consistent with the primary analyses.

Relaxation of extreme blood pressure exclusion criteria:** Refitting the models after relaxing the exclusion criteria for extreme blood pressure values yielded no substantial changes in the main effect sizes, significance levels, or directions of association.

Collectively, these sensitivity analyses confirm that the core conclusions regarding the associations of altitude and ethnicity with blood pressure and hypertension are robust and not materially affected by sample composition or extreme values.

4. Discussion

This study of 6,548 participants from an occupational health screening population on the Qinghai–Tibetan Plateau systematically examined the independent and interactive effects of altitude and ethnicity on blood pressure and hypertension. After rigorous adjustment for age, sex, BMI, dyslipidemia, and dysglycemia, we found that altitude was an independent protective factor, with moderate altitude (2,500–3,500 m) associated with a 58.3% reduction (OR = 0.417) and high altitude (3,500–4,500 m) with a 30.5% reduction (OR = 0.695) in hypertension risk compared with low altitude.

These findings diverge from the conventional view that high altitude is a risk factor for hypertension [8,9,17]. The discrepancy likely reflects differences in adaptation status: previous studies focused on short-term exposed populations, in whom acute hypoxia triggers vasoconstriction and pressure elevation [18,19]. Our participants were long-term residents with intergenerational adaptation, who have developed compensatory mechanisms—including enhanced erythropoiesis and chronic vasodilatory adaptations—that may maintain lower blood pressure [20,21]. Hemoglobin was not included as a covariate because it represents a mediating pathway of hypoxic adaptation rather than a confounder.

Ethnic differences in migration history are also relevant. Tibetans have inhabited the plateau for approximately 25,000 years, whereas other ethnic groups migrated to Qinghai only 60–650 years ago [22]. This longer residence has conferred greater hypoxic adaptation [23,24], manifesting as stable sympathovagal balance, attenuated oxidative stress, efficient tissue oxygen

utilization, and optimized salt–water homeostasis [25–28]. These traits underpin the lower blood pressure and reduced hypertension risk observed in Tibetans above 2,500 m. In contrast, Han populations, despite some acclimatization, exhibit more pronounced cardiovascular stress responses to hypobaric hypoxia, and when combined with obesity or dysglycemia, their pressure regulation is more susceptible to abnormal deviation.

Our ANCOVA demonstrated significant altitude–ethnicity interactions for both SBP and DBP, indicating ethnic specificity in the blood pressure response to altitude. Simple main effects analysis showed that at low altitude, Han and Tibetan pressures were similar; at moderate altitude (2,500–3,500 m), Tibetan SBP and DBP were significantly lower, with the ethnic difference peaking; at high altitude, both groups showed compensatory pressure increases, narrowing the difference. This pattern suggests that moderate altitude represents the range where ethnic differences in hypoxic adaptation are most fully expressed. Under mild-to-moderate hypoxia, genetic adaptive advantages are fully manifested; under extreme hypoxia, compensatory pressure elevation to maintain vital organ perfusion predominates, partially masking phenotypic differences.

Notably, we observed inconsistent patterns between continuous blood pressure and hypertension status. ANCOVA revealed significant altitude–ethnicity interactions for SBP and DBP, yet the overall interaction in the full-population logistic regression was non-significant ($P = 0.166$). This apparent contradiction can be explained by a threshold effect: ethnic differences in blood pressure distribution exist, but are predominantly within the normal range (<140/90 mmHg) and do not translate into significant heterogeneity in the risk of crossing the diagnostic threshold. Thus, the Tibetan blood pressure advantage at moderate altitude represents a physiological "quantitative change" rather than a disease-risk "qualitative change." This interpretation is supported by stratified analyses showing stronger Tibetan protection at all altitudes (moderate OR = 0.262 vs. Han 0.389).

The non-significant ethnicity main effect in logistic regression suggests that hypertension, as a multifactorial disease, is primarily driven by traditional risk factors—advancing age, central obesity, dysglycemia, and urbanization—while ethnic differences reflect continuous physiological adaptive characteristics rather than determinants of disease occurrence.

Several limitations should be acknowledged. First, selection bias: participants were predominantly government and public institution employees (78.6% college-educated), with health awareness and healthcare access differing markedly from ordinary highland residents (herders, farmers, self-employed). Thus, our findings represent discoveries in a specific occupational population and require validation in community-based samples. Second, altitude exposure was subject to non-differential misclassification, as it was assigned by county seat elevation rather than actual residential altitude. This typically biases associations towards the null, suggesting the true protective effect may be stronger than observed. Future studies should employ GPS or DEM to obtain individual residential altitudes. Third, we did not collect lifestyle data (dietary sodium, smoking, alcohol, physical activity), which may introduce residual confounding. Additionally, the cross-sectional design precludes causal inference, and we lacked

key physiological measurements (oxygen saturation, RAAS activity, endothelial function, sleep-disordered breathing) to elucidate molecular mechanisms. Prospective cohort studies integrating genomics, phenotyping, and environmental monitoring are needed to further clarify ethnic differences in high-altitude blood pressure regulation.

5. Conclusions

1. In this occupational health screening population on the Qinghai–Tibetan Plateau, blood pressure levels and hypertension prevalence demonstrate significant altitudinal and ethnic disparities. Tibetans exhibit relatively lower blood pressure levels, with the most pronounced hypertension protection at moderate altitudes.

2. A significant altitude–ethnicity interaction was observed for blood pressure levels, with the Han–Tibetan difference in blood pressure being most prominent at 2,500–3,500 m.

3. Hypertension prevalence is primarily influenced by altitude, age, obesity, and dysglycemia, while ethnic differences largely reflect physiological adaptations to hypoxia.

4. For hypertension prevention and control among similar occupational populations in high-altitude regions, differentiated strategies should be implemented based on both altitudinal gradients and ethnic characteristics. Given the higher hypertension prevalence and larger proportion of Han individuals in the low-altitude group, it is recommended to strengthen screening and intervention for traditional risk factors (obesity, dysglycemia, etc.) in this population.

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1.

Summary Table

What is known about the topic	What this study adds
The association between high-altitude residence and hypertension remains inconsistent across studies, with some reporting increased risk, others decreased risk, and still others a U-shaped relationship.	In an occupational health screening population on the Qinghai–Tibetan Plateau, higher altitude was an independent protective factor against hypertension, with the strongest effect at moderate altitude (2,500–3,500 m; OR = 0.417, 95% CI: 0.329–0.530).
Most existing studies have examined the effects of altitude or ethnicity on hypertension in isolation, without systematically exploring their interactive effects.	A significant altitude–ethnicity interaction was observed for continuous systolic and diastolic blood pressure (P = 0.022 and P < 0.001, respectively), with the Han–Tibetan difference peaking at moderate altitude.
Tibetans are known to possess genetic adaptations to high-altitude hypoxia, but the quantitative protective effect of these adaptations on blood pressure and hypertension risk has not been well characterized.	Tibetans exhibited stronger hypertension protection than Han at all altitudes, particularly at moderate altitude (OR = 0.262 vs. 0.389), suggesting that ethnic differences primarily reflect physiological adaptation to hypoxia rather than differential disease risk.

Data Availability Statement

The datasets generated and/or analyzed during the current study are not publicly available due to institutional privacy restrictions but are available from the corresponding author on reasonable request.

Author Contributions

Shenggui QI: Conceptualization, Data curation, Formal analysis, Writing – original draft. Li Li: Methodology, Investigation, Resources. Yuhua Yan: Validation, Visualization, Writing – review & editing. Hongguang Fan: Supervision, Project administration, Funding acquisition. All authors reviewed and approved the final manuscript.

Ethical Approval: This retrospective study was approved by the Medical Ethics Committee of Qinghai Cardio-Cerebrovascular Specialty Hospital, which waived the requirement for informed consent due to the retrospective nature of the study.

Competing Interests: The authors declare no competing interests.