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Study on the facial spectrum and color characteristics of patients with essential hypertension

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ABSTRACT

Objective To investigate the facial spectrum and color characteristics of patients with essential hypertension post administering antihypertensive drugs, establish a classification and evaluation model based on the facial colors of the enrolled patients, and perform in-depth analysis on the important characteristics of their facial spectrum.

Methods From September 3, 2018, to March 23, 2024, participants with essential hypertension (receiving antihypertensive medication treatment, hypertension group) and normal blood pressure (control group) were recruited from the Cardiology Department of Shanghai Hospital of Traditional Chinese Medicine, the Coronary Care Unit of Shanghai Tenth People's Hospital, the Physical Examination Center of Shuguang Hospital Affiliated to Shanghai University of Traditional Chinese Medicine, and the Gaohang Community Health Service Center. This study employed the propensity score matching (PSM) method to reduce study participants selection bias. Spectral information in the facial visible light spectrum of the subjects was collected using a flame spectrometer, and the spectral chromaticity values were calculated using the equal-interval wavelength method. The study analyzed the differences in spectral reflectance across various facial regions, including the entire face, forehead, glabella, nose, jaw, left and right zygomatic regions, left and right cheek regions as well as differences in parameters within the Lab color space between the two subject groups. Feature selection was conducted using least absolute shrinkage and selection operator (LASSO) regression, followed by the application of various machine learning algorithms, including logistic regression (LR), support vector machine (SVM), random forest (RF), Naïve Bayes (NB), and eXtreme Gradient Boosting (XGB). The reduced-dimensional dataset was split in a 7 : 3 ratio to establish a classification and assessment model for facial coloration related to primary hypertension. Additionally, model fusion techniques were applied to enhance the predictive power. The performance of the models was evaluated using metrics including the area under the curve (AUC) and accuracy. Shapley Additive exPlanations (SHAP) was used to interpret the outcomes of the models.

Results A total of 114 participants were included in both hypertension and control groups. Reflectance analysis across the entire face and eight predefined areas revealed that the

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hypertensive group exhibited significantly higher reflectance of corresponding color light in the blue-violet region ($P < 0.05$) and a lower reflectance in the red region ($P < 0.05$) compared with control group. Analysis of Lab color space parameters across the entire face and eight predefined areas showed that hypertensive group had significantly lower a and b values than control group ($P < 0.05$). LASSO regression analysis identified a total of 18 facial color features that were highly correlated with hypertension, including the a values of the chin and the right cheek, the reflectance at 380 nm and at 780 nm of the forehead. The results of the multi-model classification showed that the RF classification model was the most effective, with an AUC of 0.74 and an accuracy of 0.77. The combined model of RF + LR + SVM outperformed a single model in their classification performance, achieving an AUC of 0.80 and an accuracy of 0.76. SHAP model visualization results indicated that the top three contributors to ideal prediction results based on the characteristics from the facial spectrum were the reflectance at 380 nm across the entire face and of the nose as well as the a value of the chin.

Conclusion Within the same age group, patients with essential hypertension exhibited significant and regular changes in facial color and facial spectral reflectance parameters after the administration of antihypertensive drugs. Furthermore, facial reflectance indicators, such as the overall reflectance at 380 nm and the a value of the chin, could offer valuable references for clinically assessing the drug efficacy and health status of patients with essential hypertension.

1 Introduction

Hypertension, a global pervasive health among adults, has being continuing to posing significant challenges to the society [1, 2]. With an estimated prevalence exceeding a quarter of the adult population worldwide, hypertension stands as a major health burden across nations and regions [3]. In China, cardiovascular diseases are the leading cause of mortality in both urban and rural populations [4], with hypertension being a pivotal risk factor for these cardiovascular and cerebrovascular diseases, as well as one of the most prevalent chronic conditions [5]. Successive surveys in China have documented a marked rise in hypertension prevalence, rising from 5.1% to 31.6%, though discrepancies in population coverage, age distribution, and diagnostic criteria employed in these surveys should be noted [4, 6]. Despite steady improvements in awareness, treatment, and control rates, which are crucial indicators of hypertension management and predictors of improved cardiovascular outcomes, these metrics in China are still not optimal in general.

Although traditional blood pressure measurement methods are widely used in clinical diagnosis and treatment as well as in home monitoring, the discomfort caused by prolonged compression at the collection site is unsuitable for scenarios requiring continuous blood pressure monitoring over extended periods. In recent years, non-contact, continuous, and non-invasive blood pressure measurement has shown broad development prospects. Imaging photoplethysmography (IPPG) employs video techniques to use the facial area as the region of interest (ROI), extracting IPPG signals for the measurements of blood pressure and heart rate [7, 8]. This method enhances the abundance of information acquired manually and improves the accuracy of predictions compared with photoplethysmography (PPG). JEONG et al. [9] demonstrated the feasibility of non-contact, high-precision blood pressure measurement using IPPG signals collected from facial skin in healthy adults. Studies on the relationship between skin color and hypertension suggested that blood pressure might be associated with skin color [10, 11]. As the heart contracts and relaxes, the content of oxygenated hemoglobin in facial capillaries changes. When light shines on the face, the absorption of light by oxygenated hemoglobin leads to variations in light reflection [12], causing slight changes in skin color. Transdermal optical imaging (TOI) captures these subtle changes in facial blood flow and uses machine learning algorithms to establish models for predicting blood pressure [13] . Therefore, changes in facial features have been emerged as potential clinical markers for auxiliary diagnosis of hypertension.

The observation of facial color, recognized for its non-invasive and convenient natures, has increasingly gained recognition as a significant method for health assessment. According to traditional chinese medicine (TCM) theory, the head and face are considered the convergence points of Qi (vital energy) and blood essence, reflecting the vitality and health status of the human body. Therefore, observing facial color to understand the abundance or depletion of the internal viscera's essence and Qi has become an indispensable aspect of TCM's diagnostic techniques for assessing human health. “The heart governs the blood vessels, and its vitality is manifested in the face”. This statement suggests the close relationship between the face and the heart. However, ancient diagnosis according to facial color in TCM relies merely on visual observation and the comparison of colors to other objects’, which is susceptible to subjective factors and prone to overlooking subtle differences in colors. In contrast, modern clinical diagnosis employing facial color is realized through the use of various acquisition equipment, digitization of the indicators of facial color. This approach not only compensates for the limitations of visual observation but also enhances the depth of ancient facial diagnostic techniques, serving as a vital tool for assessing health status of human body [14], differentiating syndromes [15], and recognizing regular patterns of facial colors [16]. In the field of spectral analysis, visible light spectroscopy stands as one of the important methods of color measurement [17], offering greater accuracy than digital image technology [18]. As TCM diagnostics evolve towards objectivity, visible light spectroscopy has facilitated the digitization of facial diagnosis, advancing its application in clinical settings [19]. However, there is still insufficient scientific evidence to confirm the correlation between facial color and the use of antihypertensive drugs in patients with essential hypertension.

This study hence analyzed the indicators of facial color reflected by a spectrum of patients with essential hypertension after the administration of antihypertensive medications, explored the changes in facial color patterns acquired at different regions on the face of the enrolled patients, and further investigated the establishment of a model for distinguishing the facial colors of patients with essential hypertension. The aim is to provide an objective reference for auxiliary diagnosis of enssential hypertension and evaluation of drug efficacy using facial colors in clinical settings.

2 Data and methods

2.1 Data source

From September 3, 2018, to March 23, 2024, we recruited patients with essential hypertension who had been receiving antihypertensive medications and normotensive participants from four clinical centers: the Cardiology Department of Shanghai Hospital of Traditional Chinese Medicine, the Coronary Care Unit of Shanghai Tenth People's Hospital, the Physical Examination Center of Shuguang Hospital Affiliated to Shanghai University of Traditional Chinese Medicine, and Gaohang Community Health Service Center. For each participant, we collected information including profile numbers, names, genders, ages, diagnostic results, and blood test results, and analyzed their facial spectrum. To minimize selection bias, propensity score matching (PSM) was employed to equalize the distribution of age and gender between groups. All eligible participants signed informed consent forms prior to data collection. This study was approved by the Ethics Committee of Shuguang Hospital Affiliated to Shanghai University of Traditional Chinese Medicine, (2018-626-55-01), and registered with the clinical registration number ChiCTR1900026008.

2.2 Diagnostic criteria

According to the Chinese Guidelines for Prevention and Treatment of Hypertension (Revised Edition 2024) [20], hypertension can be diagnosed if the systolic blood pressure is ⩾ 140 mmHg and/or the diastolic blood pressure is ⩾ 90mmHg.

2.3 Inclusion and exclusion criteria

Inclusion criteria for hypertension group: (i) complied with the aforementioned mentioned diagnostic criteria for hypertension; (ii) aged between 20 and 82 years old; (iii) having been receiving stable-dose antihypertensive medication (calcium channel blockers, angiotensin receptor blockers, angiotensin-converting enzyme inhibitors, or beta-blockers) for more than one year prior to the study; (iv) no coexisting severe diseases such as heart valve disorders, renal diseases, or cerebral diseases; (v) signed the informed consent form.

Inclusion criteria for control group: (i) office blood pressure less than 140/90 mmHg; (ii) without serious failures or tumor in the heart, liver, and kidney that might affect facial colors; (iii) signed the informed consent form.

Exclusion criteria: (i) those with congenital heart disease, heart valve disorders, kidney disease, brain disease, or other serious conditions; (ii) those whose facial skin were covered (due to makeup, hair, beard, scars, wrinkles, and birthmarks); (iii) those with facial skin diseases or skin allergies; (iv) those with occupation-related changes in facial colors.

2.4 Research grouping

We divided the data based on the initial blood pressure measurements recorded in participants' medical records. Participants who met the diagnostic criteria for hypertension were included in hypertension group, and those whose blood pressure were detected normal were classified as control group. Meanwhile, samples that meet the exclusion criteria were further excluded. In this study, an upper arm electronic blood pressure monitor was employed to measure the blood pressure of participants. In addition, their facial spectrums were collected as well on the same morning measuring blood pressure.

2.5 Facial visible spectrum data collection

2.5.1 Data acquisition The visible light reflection spectroscopy system, a flame spectrometer (Ocean Optics, Miniature Spectrometer), was used to collect visible light spectral data from the faces of participants (Figure 1). This instrument has a detection range of 200 – 850 nm, an optical resolution of approximately 1.5 nm, and an integration time that varies from 1 ms to 65 s. The supporting equipment consisted of a tungsten halogen lamp (Ocean Optics, HL-2000), a laboratory-grade spectral reflectance probe, a standard diffuse reference whiteboard (Ocean Optics, WS-1), a spectra suite software for data analysis, and an auxiliary probe for data acquisition.

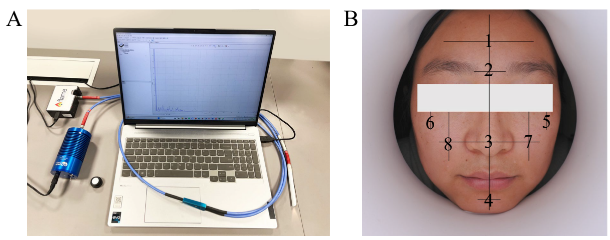

Figure 1 Visible spectrum data acquisition
A, visible light reflection spectroscopy system. B, facial sampling points. 1, forehead. 2, glabella. 3, nose. 4, jaw. 5, left zygomatic region. 6, right zygomatic region. 7, left cheek region. 8, right cheek region.

The acquisition process is as follows. (i) Before acquisition, the standard diffuse reference whiteboard WS-1 was used to save both bright and dark spectra, verifying the stability and flatness of the 100% and 0% baselines. (ii) During acquisition, the probe was sanitized with an alcohol swab, and participants were instructed to sit upright with their eyes naturally closed and foreheads exposed. The acquisition auxiliary device was placed at each facial acquisition site (Figure 1B) in sequence at a 45° angle. The sampling sites were established based on the traditional facial color zones described in the *Inner Cannon of Huangdi* (*Huang Di Nei Jing*, 《黄帝内经》). Eight specific regions were selected for spectral data collection: forehead region, glabella, nose, jaw region, left and right zygomatic regions, and left and right cheek regions. These regions were chosen based on their diagnostic significance in TCM theory. The acquisition process was conducted within a wavelength range of 380 – 780 nm, with an integration time of 170 ms and an averaging of 10 times. (iii) When the spectral reflectance curve on the software interface stabilized, the spectrum of the corresponding area was saved. The process was finished under the ambient temperature and indoor lighting conditions of either hospital wards or communities.

2.5.2 Data analysis For each participant, spectral data were collected from eight facial regions (Figure 2A) and converted to Lab colorimetric features following the International Commission on Illumination (CIE) [21]. To calculate the CIE Lab spectral chroma of facial color, this study adopts the method recommended in “CIE 15-2004: Colorimetry” [17], in the CIE 1964 supplementary colorimetric system, the tristimulus values X_{10}, Y_{10}, and Z_{10} of the standard colorimetric observer's spectral responses are converted into Lab colorimetric characteristics using equal wavelength interval weighting. In this context, L represents the lightness component of the color; a signifies the chromaticity component ranging from green to red, with positive values indicating facial coloration (higher values indicate a more tense red hue, while lower values suggest a lighter red hue); and b represents the chromaticity component ranging from blue to yellow, also with positive values for facial coloration (higher values indicate a more pronounced yellow tone, while lower values suggest a lighter yellow). The chromatic expression of facial color is a comprehensive reflection of these three chromaticity components (Figure 2B). To process the spectral data, reflectance values were sampled at 20 nm intervals across the visible spectrum (380 – 780 nm), yielding 1 192 spectral bands. The mean reflectance of all eight facial regions was calculated to represent the overall facial spectral characteristics. As our spectral collection method was point-based, we analyzed both individual regions and overall facial characteristics to provide comprehensive evaluation of facial color features.

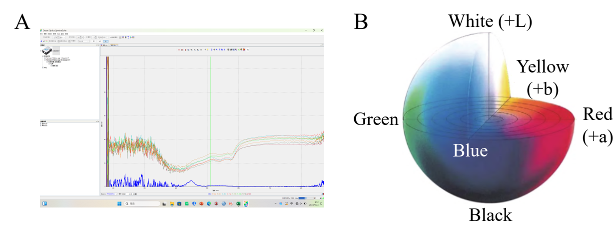

Figure 2 Calculation of the chroma of the facial colors in the spectrum
A, schematic diagram of the original visible light spectrum of the face. B, schematic diagram of the Lab color space.

2.6 Establishment and performance evaluation of the model for classifying and assessing essential hypertension

By applying the least absolute shrinkage and selection operator (LASSO) for reducing dimensionality on the spectral dataset, we obtained a reduced dataset, which was then divided into a training set and a test set in a 7 : 3 ratio. Five machine learning algorithms, including logistic regression (LR), support vector machine (SVM), random forest (RF), Naïve Bayes (NB), and eXtreme Gradient Boosting (XGB), were employed to establish a model for classifying and assessing the facial colors of patients with essential hypertension based on the spectral data collected from eight facial regions. In this study, decision-level fusion was applied to three established models that demonstrated the best overall performance, and an enhanced fusion model was thus constructed. The final binary classification results were obtained by calculating the average of the prediction probabilities for each model and converting these averages into the final classification outcomes. The accuracy, precision, F1 score, recall, and area under curve (AUC) were utilized to evaluate the prediction performance of the model. To elucidate the model’s importance and the contribution of each feature, we employed Shapley Additive exPlanations (SHAP) to quantify the impact of each feature on the prediction results, thereby providing insights into the interpretation of the outcomes yielded by the model.

2.7 Statistical analysis

Statistical analysis was performed using SPSS 24.0 software. Quantitative date were represented using the mean ± standard deviation (SD). If the variables between groups met the criteria of normality and homogeneity of variance, independent sample *t* tests and one-way analysis of variance (ANOVA) were applied for comparison. If the variables did not meet these criteria, the Mann-Whitney *U* test was used for comparing the means of two samples, while the Kruskal-Wallis *H* test was used for comparisons among three groups. Count data were expressed as frequencies and percentages, and Chi-square test was used to compare categorical variables. $P < 0.05$ was considered statistically significant.

3 Results

3.1 Basic information comparison

A total of 114 hypertensive patients (hypertension group) were matched with 114 non-hypertensive participants (control group). All participants in control group presented within-normal-range blood test results, excluding those whose facial color reflected by spectrum was impacted by the presence of diseases other than hypertension. After PSM, there were no statistically significant differences in gender and age between the two groups ($P > 0.05$, Table 1).

Table 1 Comparison of basic information between hypertension and control groups ($n = 114$)

Group	Age (year)	Gender [n (%)]	
		Male	Female
Hypertension	63.64 ± 10.47	47 (41.2)	67 (58.8)
Control	63.80 ± 10.49	47 (41.2)	67 (58.8)
P value	0.60	1.00	

3.2 Comparison of facial spectral reflectance between hypertension and control groups

When considering the overall skin color within the wavelength range of 380 – 480 nm, hypertension group exhibited higher reflectance compared with control group ($P < 0.05$), indicating that greater reflectance in the blue-violet light region for hypertension group at corresponding wavelengths. Conversely, within the wavelength range of 660 – 780 nm, hypertension group showed lower reflectance than control group ($P < 0.05$), indicating reduced reflectance in the red light region for hypertension group at corresponding wavelengths (Figure 3A).

Similarly, significant differences were observed in the spectral reflectance rates across the eight different facial areas. In the blue-violet light region, hypertension group demonstrated a higher reflectance rate for corresponding color light, including the forehead region at 380 and 420 – 500 nm; the glabella at 380 – 500 and 540 nm; the nose at 380 – 480, 540 and 580 nm; the jaw region at 380 and 500 – 540 nm; the left zygomatic region at 380 – 400, 440, 540, and 580 nm; the right zygomatic region at 380 nm; the left cheek region at 380 nm; the right cheek region at 380 – 440 nm. In the red light region, hypertension group exhibited a lower reflectance rate for corresponding color light, including the nose at 640 – 780 nm; the jaw region at 680 – 780 nm; the right zygomatic region at 700 nm; the left cheek region at 640 – 780 nm; the right cheek region at 640 – 780 nm (Figure 3B – 3I, Supplementary Table S1 – S8).

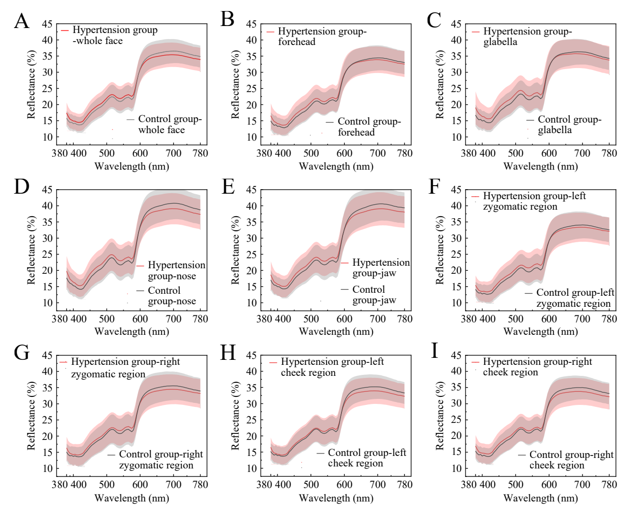

Figure 3 Comparison of facial spectral reflectance between hypertension and control groups
A, whole face. B, forehead. C, glabella. D, nose. E, jaw. F, the left zygomatic region. G, the right zygomatic region. H, the left cheek region. I, the right cheek region. The horizontal axis represents the wavelength range of 380 – 780 nm, while the vertical axis indicates spectral reflectivity, ranging from 0 to 100%. The solid lines represent the mean spectral reflectivity for both the hypertensive and control groups at different wavelengths. The shaded areas represent the range of standard deviations for both groups.

3.3 Comparison of facial spectral chromaticity between hypertension and control groups

The mean L, a, and b values of colors in the eight facial regions can collectively represent the overall facial colorimetry. The a and b values in hypertension group were both lower than those in control group ($P < 0.05$), whereas there was no significant difference in L values between the two groups ($P > 0.05$) (Table 2).

When comparing the two groups within the same facial color region, the a value showed significant differences across various color regions ($P < 0.05$), with hypertension group consistently exhibiting a lower a value than control group. The hypertension group showed

Table 2 Comparison of overall facial chromaticity between hypertension and control groups ($n = 114$)

Group	L value	a value	b value
Control	56.19 ± 3.72	11.00 ± 2.42	13.72 ± 1.97
Hypertension	56.68 ± 3.71	9.43 ± 2.42	12.7 ± 2.55
t value	1.01	– 4.68	– 3.46
P value	0.32	< 0.001	0.001

Data were represented as mean ± SD.

significantly lower b values compared with control group in all regions except the zygomatic region ($P < 0.05$) (Figure 4).

3.4 Comparison of facial colorimetric values across the eight facial regions between hypertension and control groups

3.4.1 Comparison of L, a, and b values across eight facial regions in control group In control group, the nose and jaw regions showed significantly higher L values compared with forehead and left zygomatic region ($P < 0.05$). Additionally, the glabella showed significantly higher L value compared with left zygomatic region ($P < 0.05$). The nose and jaw regions showed significantly higher a values compared with other facial areas ($P < 0.05$). The forehead showed significantly lower a value compared with the left zygomatic regions ($P < 0.05$). The nose, jaw and forehead regions showed significantly higher b values compared with the glabella and both cheek regions ($P < 0.05$) (Table 3). In a comprehensive analysis of facial color in the eight facial regions, control group showed higher L, a, and b values in the nose compared to other areas. Conversely, the left zygomatic region exhibited a lower L value, the forehead had a lower a-value, and the glabella had a lower b value compared to the rest of the facial areas. These findings suggested that the nose was a distinctive point for facial color in control group, exhibiting higher levels of brightness, redness, and yellowness compared with other facial regions.

3.4.2 Comparison of L, a, and b values across the eight facial regions in hypertension group In hypertension group, the nose and jaw regions showed significantly

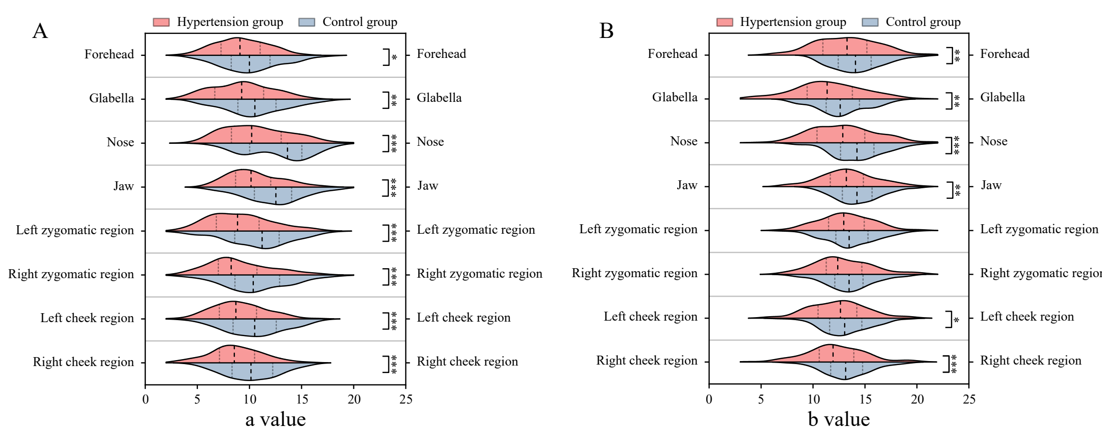

Figure 4 Comparison of chromaticity in the same facial region between the two groups

A and B, comparison of a and b values in the same facial area between the two groups, respectively. The abscissa represents a and b values, while the ordinate represents eight facial areas. Data are presented as median (P_{25}, P_{75}). The asterisks (*) indicate the presence of statistically significant differences ($^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$).

Table 3 Comparison of facial spectral chromaticity across different facial regions in control group

Facial region	L value	a value	b value
Forehead	$55.10 \pm 3.65^{\triangle\triangle\blacktriangle\blacktriangle}$	$10.18 \pm 2.81^{\triangle\triangle\blacktriangle\blacktriangle}$	14.29 ± 2.33
Glabella	56.75 ± 3.95	$10.60 \pm 2.92^{\triangle\triangle\blacktriangle\blacktriangle}$	$12.81 \pm 2.38^{\#\#\triangle\triangle\blacktriangle\blacktriangle}$
Nose	57.62 ± 4.48	12.84 ± 2.99	14.35 ± 2.45
Jaw	57.30 ± 4.68	12.38 ± 2.81	14.35 ± 2.13
Left zygomatic region	$54.53 \pm 4.45^{**\triangle\triangle\blacktriangle\blacktriangle}$	$10.88 \pm 3.08^{\#\triangle\triangle\blacktriangle\blacktriangle}$	13.69 ± 2.40
Right zygomatic region	$55.84 \pm 4.59^{\triangle}$	$10.71 \pm 3.09^{\triangle\triangle\blacktriangle\blacktriangle}$	13.50 ± 2.33
Left cheek region	55.86 ± 4.03	$10.56 \pm 2.78^{\triangle\triangle\blacktriangle\blacktriangle}$	$13.16 \pm 2.25^{\#\#\triangle\triangle\blacktriangle\blacktriangle}$
Right cheek region	55.94 ± 3.83	$10.23 \pm 2.52^{\triangle\triangle\blacktriangle\blacktriangle}$	$13.31 \pm 2.22^{\#\triangle\blacktriangle}$
t value	7.11	82.59	7.53
P value	< 0.001	< 0.001	< 0.001

Data were represented as mean ±SD. $^{\#}P < 0.05$ and $^{\#\#}P < 0.01$, compared with the forehead. $^{**}P < 0.01$, compared with the glabella. $^{\triangle}P < 0.05$ and $^{\triangle\triangle}P < 0.01$, compared with the nose. $^{\blacktriangle}P < 0.05$ and $^{\blacktriangle\blacktriangle}P < 0.01$, compared with the jaw.

higher L values compared with forehead, left zygomatic, and left cheek regions ($P < 0.05$). In addition, the glabella showed higher L value compared with forehead and left zygomatic regions ($P < 0.05$). The nose and jaw regions showed significantly higher a values compared with all other facial regions ($P < 0.05$). The glabella showed significantly lower b value compared with all other facial regions, with the exception of the cheeks ($P < 0.05$) (Table 4). When assessing the color characteristics of all eight facial regions collectively, hypertension group exhibited higher L value and a value in the nose and a higher b value in the jaw region compared with the rest of the regions. In contrast, the L value in the left zygomatic region, the a value in the right zygomatic region, and the b value in the glabella were lower than those in other facial regions. These findings suggested that the nose was characterized by higher levels of brightness and redness than other facial regions in hypertension group. On the other hand, the glabella was marked by a lower yellowness value compared with other facial regions.

Table 4 Comparison of facial spectral chromaticity across the eight facial regions in hypertension group

Facial region	L value	a value	b value
Forehead	$55.68 \pm 4.08^{*\triangle\triangle\blacktriangle\blacktriangle}$	$9.21 \pm 2.46^{\triangle\triangle\blacktriangle\blacktriangle}$	$13.21 \pm 3.05^{**}$
Glabella	57.55 ± 4.33	$9.23 \pm 2.88^{\triangle\triangle\blacktriangle\blacktriangle}$	11.52 ± 3.31
Nose	58.30 ± 4.49	10.70 ± 3.16	$12.92 \pm 3.17^{**}$
Jaw	57.96 ± 4.44	10.43 ± 2.51	$13.37 \pm 2.70^{**}$
Left zygomatic region	$55.34 \pm 4.79^{**\triangle\triangle\blacktriangle\blacktriangle}$	$9.10 \pm 2.98^{\triangle\triangle\blacktriangle\blacktriangle}$	$13.13 \pm 2.56^{**}$
Right zygomatic region	$56.33 \pm 4.61^{\triangle}$	$9.02 \pm 2.99^{\triangle\triangle\blacktriangle\blacktriangle}$	$12.87 \pm 2.80^{*}$
Left cheek region	$56.06 \pm 4.04^{\triangle\triangle\blacktriangle}$	$9.02 \pm 2.53^{\triangle\triangle\blacktriangle\blacktriangle}$	12.43 ± 2.72
Right cheek region	$56.24 \pm 4.01^{\triangle}$	$8.72 \pm 2.55^{\triangle\triangle\blacktriangle\blacktriangle}$	12.17 ± 2.86
t value	7.30	45.20	5.27
P value	< 0.001	< 0.001	< 0.001

Data were represented as mean ± SD. $^{*}P < 0.05$ and $^{**}P < 0.01$, compared with the glabella. $^{\triangle}P < 0.05$ and $^{\triangle\triangle}P < 0.01$, compared with the nose. $^{\blacktriangle}P < 0.05$ and $^{\blacktriangle\blacktriangle}P < 0.01$, compared with the jaw.

3.5 Construction and evaluation of the model for distinguishing patients with essential hypertension

In dealing with a high-dimensional dataset consisting of 756 indicators derived from the facial spectrum of the participants, LASSO regression was utilized for selecting color features. This method adjusted the complexity of the model through the λ value, where a larger λ value enhanced variable shrinkage, resulting in a streamlined model. At the λ value resulting in the minimum mean squared error (MSE) of 0.020, 18 variables were identified as highly correlated with hypertension (Figure 5). These variables were a-1, a-3, a-4, a-8, 380-1, 780-1, 380-3, 385-3, 630-3, 650-3, 655-3, 620-4, 380-7, 415-7, 625-7, 380-8, 385-8, and 380-mean.

Based on the feature variables selected by the LASSO algorithm, we constructed a model for identifying facial color of patients with essential hypertension (Table 5). According to these modeling results, the top three models ranked by classification accuracy are RF, LR, and SVM. Notably, the RF model achieved an AUC of 0.74. In this study, decision-level fusion was conducted for the aforementioned three models, which exhibited the best overall performance. Fusion models were constructed for RF + LR, RF + SVM and RF + LR + SVM, respectively. In the fusion models, the RF + LR + SVM model exhibited the best performance of all, with an AUC of 0.80.

To provide an intuitive explanation of how the selected variables contributed to the prediction of hypertension, we employed SHAP to visualize their impacts. Figure 6A ranks these 18 risk factors based on their average absolute SHAP values, where the SHAP values on the x-axis represents the importance of each factor in the prediction model. As can be seen from the figure, average facial spectral reflectance at 380 nm (380-mean), jaw a-value (a-4) and nasal spectral reflectance at 380 nm (380-3) have more pronounced effects on the model. Figure 6B presents a scatter plot showcasing the SHAP values of each feature in each sample, illustrating whether facial color parameter values positively or negatively influence the classification outcome of hypertension. The red direction on the right side of the plot indicates a positive effect of the feature on the model's prediction, and vice versa. In other words, when all red dots are on the right, it signifies that higher feature values are associated with an increased risk. Conversely, when all blue dots are on the right, it indicates that lower feature values are linked to an increased risk. The results demonstrate that the blue dots of 380-mean and 380-3 are mainly on the left, indicating that lower reflectivity values at 308 nm in the whole face and nose are associated with lower hypertension risk, while the high-value red dots of a-4 are on the left, the lower the a-4 value, the higher the risk of hypertension. At the same time, high-value red dots of 380-1,

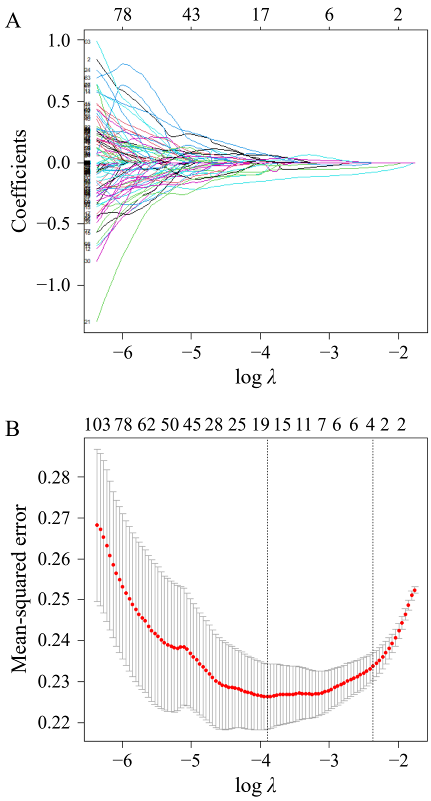

Figure 5 LASSO regression analysis on facial spectral characteristics in essential hypertension

A, the variation in the coefficients of the independent variables as the penalty parameter λ varies. B, the evolution of independent variable selection as the penalty parameter λ changes. The vertical axis represents mean squared error, while the top horizontal axis shows the number of independent variables, and the bottom horizontal axis displays the corresponding log λ values for different λ values. Vertical dashed lines are drawn at the minimum mean squared error (λ = 0.020) and the standard error of the minimum distance (λ = 0.938). The naming convention for variables is represented as "chromaticity symbol in Lab color space or spectral wavelength + facial acquisition area". For example, a-1, indicates forehead a value; 380-1, indicates forehead spectral reflectance at 380 nm; 380-mean, average facial spectral reflectance at 380 nm.

Table 5 Performance of the models for distinguishing primary hypertension based on facial color characteristics in the facial spectrum

Model	Accuracy	AUC	Precision	Recall	F1 score
RF	0.77	0.74	0.73	0.85	0.78
LR	0.72	0.81	0.67	0.88	0.76
SVM	0.71	0.78	0.69	0.74	0.71
NB	0.60	0.68	0.62	0.53	0.57
XGB	0.68	0.67	0.67	0.71	0.69
RF + LR	0.75	0.79	0.91	0.69	0.78
RF + SVM	0.75	0.74	0.82	0.72	0.77
RF + LR + SVM	0.76	0.80	0.91	0.70	0.79

780-1, 385-3, 380-8, 385-8 and other indicators were located on the right side, suggesting that when these indicators increased, the risk of hypertension also increased.

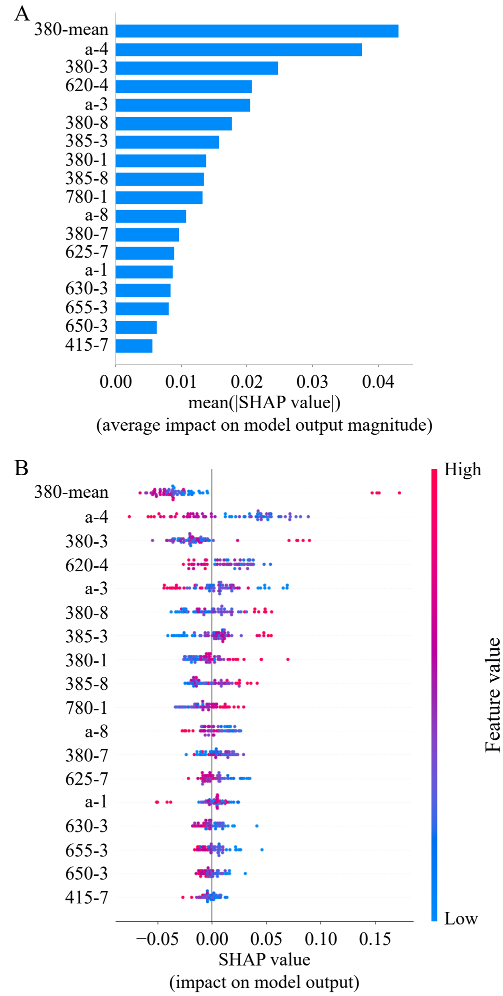

Figure 6 SHAP analysis of the facial color classification model

A, the ranking of feature importance indicated by SHAP. B, feature attributes in SHAP. On the left side of the graph are the names of the facial color parameters, each row reflecting the influence of that parameter. On the right side are the numerical values of the feature attributes, with red indicating a high feature value and blue indicating a low feature value. Each point represents a sample, and areas where points are dense indicate a large number of samples clustering. The horizontal axis represents the SHAP value, and the magnitude of the value indicates the influence of the feature on the result.

4 Discussion

Facial diagnosis in TCM with the use of modern technologies has already been developed and become an extension of traditional facial diagnosis. This approach has been optimized by integrating the advantages of intelligence, informatization, and standardization as a whole. The informatization of facial diagnosis has gained significance of clinical application in disease diagnosis, TCM syndrome differentiation, and constitution identification [22]. In addition, the use of artificial intelligence in TCM facial diagnosis has been progressing to assist in clinical diagnosis and syndrome differentiation of cardiovascular diseases such as hypertension and coronary heart disease [23–25]. Essential hypertension, a prevalent cardiovascular condition, has been subjected to in-depth analysis of facial color characteristics in patients. This research has paved the way for an objective and visually based approach to diagnosing hypertension syndromes and assessing the effectiveness of treatments.

4.1 Statistical analysis of facial spectral and color features in hypertensive patients

The results showed that the red and yellow colors on the whole face and at different sampling regions in patients with essential hypertension after administering hypertensive medication were less noted compared with participants without hypertension. Regarding reflectance, hypertension group exhibited higher reflectance level of corresponding colors in the blue-violet light region, whereas the reflectance level of corresponding colors in the red light region was lower. Previous studies have found that the facial color of hypertensive patients tends to be reddish or yellowish with a red tinge, with significant differences in facial colors noted among hypertensive patients of different genders or with various disease durations [23, 24, 26, 27]. The reasons for the differences in the characteristics of facial color observed in this study compared to other studies might stem from several factors. First, all participants in this study have a history of hypertension, which can cause vasoconstriction and poor blood circulation, which have potentials leading to damages in the vascular wall and inflammatory responses [28], thereby affecting the blood circulation and oxygen delivery in the face. This resulted in decreased oxygen partial pressure in local microvessels, changes in hemoglobin absorption spectra, and a shift from the red spectral range to the blue spectral range in the visible light band, leading to particular changes in the facial diagnosis of hypertension [29]. Second, the majority of participants in this study are elderly individuals. According to TCM theories on the etiology and pathogenesis of hypertension in the elderly, the condition is predominantly attributed to deficiencies in the liver and kidneys (the root cause) and a depletion of Qi and blood.

In contrast, TCM attributes the superficial symptoms of hypertension to factors such as phlegm, blood stasis, wind, and fire [30]. Although antihypertensive medications help maintain relatively stable blood pressure levels in subjects, thereby inhibiting the manifestation of superficial symptoms on the face, the root deficiencies remain, which could potentially influence the study results. Study has shown that the brightness of facial color decreases with age in healthy individuals [31]. Since most participants in this study are elderly, this age-related decline in brightness could explain the absence of significant differences in L values (brightness) observed both overall and across various facial regions.

4.2 Modeling and analysis of hypertension based on facial color and spectrum characteristics

This study employed facial spectral colorimetry and spectral reflectance data to classify hypertension. After feature selection using LASSO regression, both the standalone RF model and the RF + LR + SVM fusion model demonstrated superior classification accuracy, with an enhancement in classification performance. This suggests that facial spectral data can, to a certain extent, aid in the classification of diseases. Furthermore, the SHAP model was employed to objectively analyze and visualize the importance of different facial spectral indicators in the modeling process, elucidating their contribution to the development of a diagnostic model for hypertension. This study identified three significant features in the model: the a value in the chin region, the average facial spectral reflectance at 380 nm, and the nasal spectral reflectance at 380 nm, highlighting the strong correlation between changes in the nose, chin, a value, and spectral reflectance at 380 nm and the presence of hypertension. Additionally, the overall distribution of facial color between hypertension and control groups was found to be broadly consistent, characterized by increased brightness in the nose region and reduced brightness in the forehead and left cheek regions. Regarding redness, the nose and chin regions exhibited higher values, and the chin region displayed greater yellowness compared with the eyebrow area. These findings align with the traditional facial diagnosis theory that the symptoms of the five zang-organs are reflected successively in the center of the nose, thereby reinforcing the utility of facial color and spectrum characteristics in diagnosing hypertension.

A comparative analysis of facial color has revealed a particular pattern in the facial spectral parameters among patients with essential hypertension after administering antihypertensive medications and across different facial regions. This pattern is in line with the theoretical etiology and pathogenesis of hypertension, suggesting that facial spectral reflectance could serve as an objective diagnostic indicator for essential hypertension. Previous scholars have conducted objective analytical studies on the facial color of patients with essential hypertension, with variations in the instruments, research populations, and study indicators used [32]. Building these efforts, this study identified subtle differences in facial color between hypertensive and non-hypertensive individuals, and employed machine learning techniques to classify patients based on their facial color characteristics. By adopting a nuanced approach and leveraging advanced machine learning algorithms, we aimed to delve into the intricacies of facial color characteristics associated with hypertension. This approach enabled us to detect subtle changes that could not be readily observed by naked eyes, thereby providing a more comprehensive and accurate assessment of facial color characteristics related to hypertension. The findings of this study can contribute to the development of non-invasive and objective diagnostic tools for hypertension, potentially enhancing early detection and intervention of the disease.

4.3 Limitations and future work

This study, however, has some limitations. First, this study did not account for the potential effects of either stable or unstable blood pressure control post medication on variations in facial color. Second, the sample size of this study was limited. Despite our diligent efforts to collect samples that would mitigate the effects of age and gender on our findings, we recognized that inherent difference in facial color between genders persist and may have influenced the results. Third, the study did not explore changes in facial color characteristics of patients with essential hypertension from multiple disease perspectives. In future studies, it would be valuable to compare the facial color and spectrum characteristics of patients with primary hypertension across various blood pressure levels, disease durations, and in the context of the same disease presenting with different syndromes. By integrating the spectral reflectivity characteristic wavelength screening method, we could isolate the spectral characteristics related to disease states. In conjunction with machine learning algorithms, a facial color classification and assessment model can be established to realize the objectification of facial diagnosis for essential hypertension.

5 Conclusion

In this study, we found that a single machine learning model, namely the RF, as well as a fusion model combining the RF, LR, and SVM, can significantly enhance the predictive performance of the facial color classification model. Objective data have confirmed the value of facial spectral parameters in classifying patients with essential hypertension. The facial color and spectral parameters can provide references for clinically assessing the efficacy of medication on patients with essential hypertension.

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Competing interests

The authors declare no conflict of interest.

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原发性高血压患者面色光谱和颜色特征研究

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【摘要】目的 探讨原发性高血压患者在服用降压药后的面色光谱和颜色特征，联合机器学习算法建立一个原发性高血压面色分类评估模型并对面色光谱特征重要性进行进一步分析。**方法** 于 2018 年 9 月 3 日至 2024 年 3 月 23 日期间，分别在上海市中医院心内科、上海市第十人民医院冠心病监护病房、上海中医药大学附属曙光医院体检中心和高行社区卫生服务中心招募原发性高血压患者（接受降压药物治疗，高血压组）和正常血压受试者（对照组）。本研究使用倾向性评分匹配方法对受试者进行匹配。使用 Flame 光谱仪采集受试者的面部可见光光谱信息，并利用等间隔波长法计算光谱色度值。本研究分析了两组受试者在面部整体、前额、眉间、鼻部、下巴、两颧部和两颊部的光谱反射率以及 Lab 色空间中参数的差异。使用最小绝对收缩和选择算子（LASSO）回归进行特征筛选，利用逻辑回归（LR）、支持向量机（SVM）、随机森林（RF）、朴素贝叶斯（NB）、极限梯度提升（XGB）等多种机器学习算法，将降维后的数据集按 7：3 的比例划分，建立原发性高血压面色分类评估模型，同时进行模型融合。以曲线下面积（AUC）、准确度等指标评估模型性能。使用夏普利加性解释（SHAP）来解释模型结果。**结果** 高血压组和对照组各纳入了 114 名研究对象。面部整体和八个采集区域的反射率分析显示，与对照组相比，高血压组在蓝紫光区域对相应色光的反射率高（$P < 0.05$），在红光区域对相应色光的反射率低（$P < 0.05$）。面部整体和八个采集区域的 Lab 色空间参数分析显示，高血压组 a 值、b 值均小于对照组（$P < 0.05$）。经过 LASSO 回归筛选，共有包括颏部的 a 值、右颊部的 a 值、庭部 380 nm 和 780 nm 的反射率等在内的 18 个面色特征被认为与高血压高度相关。多模型分类结果显示，RF 分类模型为最优模型，AUC 为 0.74，准确率为 0.77。RF + LR + SVM 模型融合较单一模型的分类性能效果好，AUC 为 0.80，准确率为 0.76。SHAP 模型可视化显示面色光谱特征对预测结果的贡献度前三的是面部整体、鼻部 380 nm 的反射率和颏部的 a 值。**结论** 在相同的年龄范围，原发性高血压患者服用降压药后，面部颜色和面部光谱反射率参数呈现出明显规律的变化。此外，面色反射率指标如面部整体 380 nm 的反射率和颏部的 a 值可以为临床评估原发性高血压患者的药物疗效及健康状况提供潜在的参考指标。

【关键词】原发性高血压；面色；可见光光谱；机器学习；夏普利加性解释