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Relationship Between Electrolyte Levels and Dipping Blood Pressure Pattern in Hypertensive Patients: A Single Center Cross-Sectional Study in Shanghai

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Background: Few studies have explored the link between body fluid ion levels (sodium, calcium, magnesium, phosphorus) and blood pressure circadian rhythm. This study investigates these ions' relationship with the dipping blood pressure pattern in hypertensive patients, highlighting their potential for monitoring electrolyte levels in hypertension management.

Methods: According to 2018 Chinese guidelines for hypertension management, hypertensive patients were classified into dipping/super-dipping and non-dipping/reverse-dipping groups based on nocturnal blood pressure decline. Clinical data and serum/24-hour urine electrolyte levels were then collected from these patients. Logistic regression and advanced statistical modeling were used to identify influencing factors.

Results: Age and alpha-blockers negatively correlate with the likelihood of dipping blood pressure in hypertensive patients ($P<0.05$). Highest chance of dipping occurs at age 54 years, with serum sodium at 139.55 mmol/L and 24-hour urinary calcium at 5.34 mmol ($P<0.05$). The lowest likelihood is at a 24-hour urinary calcium level of 1.65 mmol ($P<0.05$). The largest nocturnal systolic drop is at age 57 years, serum calcium at 2.41 mmol/L, and 24-hour urinary calcium at 5.34 mmol ($P<0.05$). The largest diastolic drop is at age 54 years, with serum sodium at 139.03 mmol/L, serum calcium at 2.42 mmol/L, and serum magnesium at 0.95 mmol/L ($P<0.05$). A serum calcium level over 2.20 mmol/L significantly boosts the chance of dipping and nocturnal diastolic drop ($P<0.05$).

Conclusion: In hypertensive patients, the chance of a dipping blood pressure pattern declines with age, possibly peaking between 54–57 years. Optimal serum sodium for dipping is 139 mmol/L, and higher serum calcium (peaking at 2.41 mmol/L) increases this likelihood. Alpha-blockers may negatively affect the dipping blood pressure pattern.

Keywords: 24-hour ambulatory blood pressure monitoring, circadian blood pressure rhythm, dipping blood pressure pattern

Introduction

Hypertension stands as a significant chronic disease globally, with high rates of incidence and prevalence, and is also a frequently encountered cardiovascular syndrome in China.[1] It is estimated that in 2010, 31.1% (1.39 billion) of the global adult population suffered from hypertension.[2] Between 1990 and 2019, the number of hypertensive patients aged 30 to 79 worldwide has doubled,[3] and the prevalence of hypertension among adults in China has reached 27.5%.[4] The circadian rhythm of blood pressure, a common rhythm of the cardiovascular system, plays a pivotal role in the progression of hypertension.[5] The normal circadian rhythm of blood pressure is characterized by a dipper pattern, where the systolic and diastolic blood pressure at night decreases by 10% to 20% compared to the daytime. A decrease of

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less than 10% is indicative of a non-dipper or reverse dipper pattern.[6] Non-dipper and reverse dipper patterns are closely associated with a decline in cardiac and renal function and an increased risk of cardiovascular mortality.[7,8]

The circadian rhythm of blood pressure in hypertensive patients may be influenced by the status of several electrolytes, including sodium, calcium, magnesium, and phosphorus. Dietary sodium intake has been shown to modulate nocturnal blood pressure decline in individuals with salt-sensitive essential hypertension.[9] Hypomagnesemia attenuates the magnitude of nocturnal blood pressure dipping and promotes a non-dipper pattern, possibly via enhanced nocturnal sympathetic activity and disruption of the renin–angiotensin–aldosterone system rhythm.[10] Dysregulated calcium–phosphorus homeostasis may also indirectly disturb blood pressure rhythmicity by impairing vascular function.[11] Nevertheless, data directly linking circulating levels of sodium, calcium, magnesium, and phosphorus to the circadian blood pressure profile in hypertensive patients remain scarce. These ions are common elements in human body fluids and are intimately connected with human water and sodium metabolism, neuroendocrine functions, and fluid balance. They can partially reflect the metabolic status of the body, and clinical data are relatively easy to obtain. Therefore, this study aims to collect comprehensive clinical data from hypertensive patients and to analyze the associations between circulating and urinary concentrations of sodium, calcium, magnesium, and phosphorus and the dipper pattern of blood pressure. By doing so, we seek to determine whether a threshold level of these electrolytes in body fluid triggers an alteration in the circadian rhythm of blood pressure.

Materials and Methods

Study Subjects and Ethical Approval

This is a single center cross-sectional study. Patients with hypertension admitted to the Department of Cardiology at Longhua Hospital Affiliated to Shanghai University of Traditional Chinese Medicine from January 2021 to December 2023 were selected for this study. The inclusion criterion was all patients who met the diagnostic criteria for hypertension as outlined in the 2018 Chinese guidelines for the management of hypertension.[12] Exclusion criteria included patients with secondary hypertension, severe renal failure and those with incomplete clinical data. Secondary hypertension and severe renal failure, both of which may substantially perturb electrolyte homeostasis, were deliberately excluded from this study. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Longhua Hospital Affiliated to Shanghai University of Traditional Chinese Medicine (approval number: 2020LCSY044). All patients voluntarily participated in the study and provided written informed consent. All enrolled patients maintained their usual diet. Based on recent national estimates, the prevalence of reverse-dipper hypertension in China is approximately 49%.[13] Using an absolute precision of ±5%, a two-sided α of 0.05, and allowing for 10% anticipated data loss, the calculated sample size was 426 participants. And after excluding cases with incomplete data, a total of 419 patients were ultimately included in the final analysis.

Study Methods

General Data Collection

Comprehensive clinical data were collected for each patient, including gender, age, hypertension duration, and the presence or absence of comorbidities such as diabetes mellitus, myocardial infarction, and cerebral infarction. Additionally, detailed records of antihypertensive medications taken by the patients were maintained, encompassing angiotensin receptor-neprilysin inhibitors (ARNI), angiotensin-converting enzyme inhibitors (ACEI), angiotensin receptor blockers (ARB), calcium channel blockers (CCB), diuretics (including thiazide and loop diuretics), mineralocorticoid receptor antagonists (MRA), beta-blockers, alpha-blockers, and clonidine. In cases where patients were using single-pill combinations, the medications were categorized based on their constituent components.

24-Hour Ambulatory Blood Pressure Monitoring and Grouping

24-hour Ambulatory blood pressure monitoring was conducted by dedicated nurse using the TM-2430 ambulatory blood pressure monitor. The cuff was secured on the patient's left upper arm, with the lower edge of the cuff positioned 2 to 3 cm above the elbow crease. The device was programmed to automatically inflate and measure blood pressure at 20-minute intervals during the day (from 8:00 to 20:00) and at 30-minute intervals at night (from 20:00 to 08:00 the following day). The nocturnal blood pressure fall rate was calculated using the formula: (Daytime average blood pressure −Nighttime average blood pressure)/Daytime average blood pressure×100%, in accordance with the 2020 Chinese Hypertension League Guidelines on Ambulatory Blood Pressure Monitoring.[6] Patients with a nocturnal blood pressure fall rate of less than 10% were categorized into the non-dipper/reverse dipper group, while those with a rate of 10% or more were classified into the dipper/over-dipper group. In cases where systolic and diastolic pressures did not align, the systolic pressure was taken as the reference standard.[14] Controlled hypertension was defined as a 24-hour ambulatory systolic/diastolic blood pressure <130/80 mmHg.[15] For each participant, data were collected continuously over a 24-hour period, beginning at 08:00 on day 1 and ending at 08:00 on the following day.

Serum and 24-Hour Urine Testing

Following a 12-hour overnight fast, venous blood samples were collected from patients at 7:00 AM the next day to measure serum concentrations of sodium, calcium, and magnesium ions. Additionally, patients were instructed to begin collecting a 24-hour urine sample starting at 6:00 AM the day after admission to assess the levels of sodium, calcium, magnesium, and phosphate ions in the urine. Venous blood samples were collected by dedicated nurses. Patients self-collected 24-hour urine into standardized containers provided by the hospital; the next day, dedicated nurses delivered these containers to the hospital laboratory for analysis. For each participant, data were collected continuously over a 36-hour interval, commencing at 19:00 on day 1 and concluding at 07:00 on day 3.

Statistical Methods

Statistical analysis was performed using SPSS 20.0 and R 4.2.2 software. For normally distributed continuous variables, the mean ± standard deviation was used for description, and the independent samples *t*-test was applied for group comparisons. For continuous variables not conforming to a normal distribution, the median (interquartile range) [M (QL~QU)] was used, and the Mann–Whitney *U*-test was employed for group comparisons. Variables that conformed to a normal distribution were age, systolic and diastolic blood pressures, the 24-hour mean systolic and diastolic blood pressures, the daytime and nighttime mean systolic and diastolic blood pressures, and serum electrolyte concentrations. Those exhibiting skewed distributions were hypertension duration, nocturnal systolic and diastolic blood pressure decline rates, and 24-hour urinary electrolyte excretion. Categorical data were described using frequencies and analyzed with the chi-square test. Univariate logistic regression analysis was conducted to assess the relationship between age, gender, diabetes, controlled hypertension, serum sodium, calcium, and magnesium concentrations, and 24-hour urine sodium, calcium, magnesium, and phosphate levels with the dipper/over-dipper group. Variables with statistically significant results in the univariate analysis were then subjected to multivariate logistic regression analysis (coding: dipper/over-dipper group = 1, non-dipper/reverse dipper group = 0). Considering the potential nonlinear relationships among these factors, we then used restricted cubic spline (RCS) analysis with four knots to examine how age, sex, diabetes, serum sodium, calcium and magnesium concentrations, as well as 24-hour urinary sodium, calcium, magnesium and phosphate excretion, are associated with (1) dipper/over-dipper status and (2) the magnitude of nocturnal systolic and diastolic blood pressure decline. The significance level was set at $P < 0.05$.

Results

Baseline Characteristics

A total of 419 patients were included in this study, comprising 224 males and 195 females. There were 116 patients in the dipper/over-dipper group and 303 in the non-dipper/reverse dipper group. The average age was 65.08 ± 13.52 years, with hypertension duration of 12.00 (6.00–22.00) years. The nocturnal decline rates for systolic and diastolic blood pressure were 4.13 (−2.19–10.94)% and 5.14 (−0.81–11.82)% respectively. The serum concentrations of sodium, calcium, and magnesium ions were 140.76 ± 2.86 mmol/L, 2.24 ± 0.20 mmol/L, and 0.88 ± 0.13 mmol/L respectively. The 24-hour urinary levels of sodium, calcium, magnesium, and phosphate ions were 138.10 (105.00–178.00) mmol, 2.51 (1.06–4.83) mmol, 3.07 (2.18–4.19) mmol, and 15.50 (11.11–20.18) mmol respectively.

Compared with the non-dipper/reverse dipper group, patients in the dipper/over-dipper group were significantly younger (P=0.005), exhibited a significantly greater nocturnal decline in systolic and diastolic blood pressure (P<0.001), had a lower 24-hour average systolic blood pressure (P=0.001), a higher daytime average diastolic blood pressure (P=0.030), and a significantly lower nighttime average systolic and diastolic blood pressure (P<0.001). The use of alpha-blockers was also lower in the dipper/over-dipper group (P=0.010), and this group had higher serum calcium ion concentrations and 24-hour urinary phosphate ion levels (P=0.030, P=0.041 respectively). No other significant differences were observed (P>0.05). See Table 1 for details.

Logistic Regression Analysis for Dipper/Over-Dipper Hypertension Pattern

Univariate logistic regression analysis was performed to examine the association between various factors and the dipper/over-dipper group. The factors included age, gender, diabetes, cerebral infarction, controlled hypertension, antihypertensive medications, serum sodium, calcium, and magnesium concentrations, and 24-hour urine sodium, calcium, magnesium, and phosphate levels. The analysis revealed that age, the use of alpha-blockers, serum calcium ion concentration,

Table 1 Baseline Characteristics of All Study Participants

Variables	Total (n=419)[a]	Dipper/Over-Dipper Group (n=116)[a]	Non-Dipper/Reverse Dipper Group (n=303)[a]	χ^2/t/Z value	*P*-value
Male/female, n	224/195	64/52	160/143	0.19	0.664[b]
Age, years	65.08 ± 13.52	62.09 ± 12.56	66.22 ± 13.71	2.83	0.005[c]
Hypertension duration, years	12.00 (6.00~22.00)	12.00 (4.00~21.00)	13.00 (7.00~22.00)	−1.64	0.101[d]
Comorbidities					
DM/no DM, n	208/211	52/64	156/147	1.49	0.223[b]
MI/no MI, n	9/410	0/116	9/294	2.25	0.134[b]
CI/no CI, n	119/300	34/82	85/218	0.07	0.798[b]
Systolic blood pressure, mmHg	143.15 ± 21.14	141.01 ± 19.38	143.97 ± 21.76	1.27	0.204[c]
Diastolic blood pressure, mmHg	82.38 ± 12.82	83.39 ± 12.95	81.99 ± 12.77	−0.99	0.323[c]
Controlled/uncontrolled hypertension, n	94/325	31/85	63/240	1.70	0.193[b]
ABPM					
Nocturnal Systolic Blood Pressure Decline Rate, %	4.13 (−2.19~10.94)	14.57 (12.67~18.68)	0.81 (−4.28~5.12)	−15.84	<0.001[d]
Nocturnal Diastolic Blood Pressure Decline Rate, %	5.14 (−0.81~11.82)	14.97 (12.05~19.72)	2.36 (−3.13~6.56)	−13.97	<0.001[d]
24-hour average systolic blood pressure, mmHg	141.29 ± 18.58	136.63 ± 16.73	143.08 ± 18.97	3.21	0.001[c]
24-hour average diastolic blood pressure, mmHg	80.30 ± 10.68	79.75 ± 9.68	80.50 ± 11.05	0.65	0.518[c]
Daytime average systolic blood pressure, mmHg	143.25 ± 18.63	143.62 ± 17.76	143.11 ± 18.98	−0.25	0.803[c]
Daytime average diastolic blood pressure, mmHg	81.58 ± 11.02	83.47 ± 10.42	80.86 ± 11.17	−2.18	0.030[c]
Nighttime average systolic blood pressure, mmHg	136.91 ± 21.85	120.40 ± 16.11	143.23 ± 20.42	12.01	<0.001[c]
Nighttime average diastolic blood pressure, mmHg	77.18 ± 12.02	70.31 ± 9.75	79.81 ± 11.79	8.40	<0.001[c]
Antihypertensive medications					
ARNI/no ARNI, n	62/357	15/101	47/256	0.44	0.506[b]
ACEI or ARB/no ACEI or ARB, n	185/234	47/69	138/165	0.86	0.354[b]
CCB/no CCB, n	314/105	93/23	221/82	2.34	0.126[b]
Diuretics/no Diuretics, n	44/375	7/109	37/266	3.41	0.065[b]
MRA/no MRA, n	28/391	4/112	24/279	2.69	0.101[b]
Beta-blockers/no Beta-blockers, n	163/256	46/70	117/186	0.04	0.845[b]
Alpha-blockers/no alpha-blockers, n	72/347	11/105	61/242	6.68	0.010[b]
Clonidine/no Clonidine, n	36/383	9/107	27/276	0.14	0.706[b]
Serum electrolytes concentration					
Sodium, mmol/L	140.76 ± 2.86	140.81 ± 2.11	140.74 ± 3.10	−0.26	0.794[c]
Calcium, mmol/L	2.24 ± 0.20	2.27 ± 0.17	2.23 ± 0.21	−2.18	0.030[c]
Magnesium, mmol/L	0.88 ± 0.13	0.89 ± 0.10	0.87 ± 0.14	−1.04	0.301[c]
24-hour urine electrolytes level					
Sodium, mmol	138.10 (105.00~178.00)	146.40 (110.68~172.50)	134.60 (100.50~178.10)	−1.14	0.256[d]
Calcium, mmol	2.51 (1.06~4.83)	3.33 (1.14~5.26)	2.28 (1.06~4.49)	−1.82	0.069[d]
Magnesium, mmol	3.07 (2.18~4.19)	3.15 (2.32~4.17)	3.06 (2.08~4.19)	−0.85	0.393[d]
Phosphate, mmol	15.50 (11.11~20.18)	17.06 (11.85~20.67)	14.90 (11.06~19.48)	−2.05	0.041[d]

Notes: [a]Mean ± standard deviation; Median (interquartile range). [b]Chi-squared test. [c]Independent samples *t*-test. [d]Mann–Whitney *U*-test.

Abbreviations: DM, diabetes mellitus; MI, myocardial infarction; CI, cerebral infarction; ABPM, 24-hour ambulatory blood pressure monitoring; ARNI, angiotensin receptor-neprilysin inhibitors; ACEI, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blockers; CCB, calcium channel blockers; MRA, mineralocorticoid receptor antagonists.

and 24-hour urine calcium ion level were significantly associated with the dipper/over-dipper group (P < 0.05), while the other factors were not (P > 0.05). Subsequently, a multivariate logistic regression analysis was conducted with these significant factors. The results indicated that age and the use of alpha-blockers were independently associated with the dipper/over-dipper group (P = 0.013, P = 0.015). For further details, refer to Table 2.

Table 2 Results of Logistic Regression Analysis for Dipper/Over-Dipper Hypertension Pattern (n=419)

Items	Univariate Logistic Regression Analysis						Multivariate Logistic Regression Analysis					
	B	SE	χ^2-value	OR[a]	95% CI[b]	*P*-value	B	SE	χ^2-value	OR[a]	95% CI[b]	*P*-value
Age	−0.022	0.008	7.712	0.98	0.96~0.99	0.005	−0.20	0.008	6.109	0.98	0.96~1.00	0.013
Sex												
Female				—	—							
Male	0.095	0.219	0.189	1.10	0.72~1.69	0.664						
DM												
No				—	—							
Yes	−0.267	0.219	1.484	0.77	0.50~1.18	0.223						
CI												
No				—	—							
Yes	0.061	0.241	0.065	1.06	0.66~1.70	0.798						
Controlled hypertension												
No												
Yes	0.329	0.253	1.688	1.39	0.85~2.28	0.194						
ARNI												
No				—	—							
Yes	−0.212	0.319	0.442	0.81	0.43~1.51	0.506						
ACEI or ARB												
No				—	—							
Yes	−0.205	0.222	0.859	0.81	0.53~1.26	0.354						
CCB												
No				—	—							
Yes	0.406	0.266	2.319	1.50	0.89~2.53	0.128						
Diuretics												
No				—	—							
Yes	−0.773	0.428	3.267	0.46	0.20~1.07	0.071						
MRA												
No				—	—							
Yes	−0.879	0.552	2.540	0.42	0.14~1.22	0.111						
Beta-blockers												
No				—	—							
Yes	0.044	0.223	0.038	1.04	0.67~1.62	0.845						
Alpha-blockers												
No				—	—					—	—	
Yes	−0.878	0.348	6.373	0.42	0.21~0.82	0.012	−0.867	0.356	5.925	0.42	0.21~0.85	0.015
Clonidine												
No				—	—							
Yes	−0.151	0.401	0.142	0.86	0.39~1.89	0.707						
Serum electrolytes												
Sodium	0.009	0.039	0.049	1.01	0.94~1.09	0.824						
Calcium	1.262	0.618	4.170	3.53	1.05~11.86	0.041	1.019	0.589	2.991	2.77	0.87~8.80	0.084
Magnesium	0.885	0.878	1.015	2.42	1.26~3.85	0.314						
24-hour urine electrolytes												
Sodium	0.002	0.001	2.312	1.00	1.00~1.01	0.128						
Calcium	0.071	0.042	2.803	1.07	0.99~1.07	0.094						
Magnesium	0.066	0.070	0.873	1.07	0.93~1.23	0.350						
Phosphate	0.027	0.015	3.213	1.03	1.00~1.06	0.073						

Notes: [a]OR, Odds Ratio; [b]CI, Confidence Interval.
Abbreviations: DM, diabetes mellitus; CI, cerebral infarction; ARNI, angiotensin receptor-neprilysin inhibitors; ACEI, angiotensin-converting enzyme inhibitors; ARB, angiotensin receptor blockers; CCB, calcium channel blockers; MRA, mineralocorticoid receptor antagonists.

Relationship Between Dipper Blood Pressure Pattern and Various Factors

Restricted cubic spline analysis was performed to examine the relationship between the dipper/over-dipper group and various factors such as age, gender, diabetes, serum sodium, calcium, and magnesium concentrations, and 24-hour urine sodium, calcium, magnesium, and phosphate levels. The results indicated that the dipper/over-dipper group was associated with age, serum sodium, calcium ion concentrations, and 24-hour urine calcium ion levels (P=0.007, P=0.005, P=0.037, P=0.018), while no significant associations were found with the other factors (P > 0.05).

Although age showed a potential linear relationship with dipper blood pressure (P for non-linearity = 0.051), the trend plot revealed a turning point at 54 years. The likelihood of dipper blood pressure was maximized at serum sodium ion concentration of 139.55 mmol/L and 24-hour urine calcium ion level of 5.34 mmol, and minimized at a 24-hour urine calcium ion level of 1.65 mmol. A serum calcium ion concentration greater than 2.20 mmol/L was significantly associated with an increased likelihood of dipper blood pressure. For more details, refer to Figure 1.

Relationship Between Nocturnal Systolic Blood Pressure Decline Rate and Various Factors

Restricted cubic spline analysis was also conducted to investigate the relationship between the nocturnal systolic blood pressure decline rate and various factors including age, gender, diabetes, serum sodium, calcium, and magnesium concentrations, and 24-hour urine sodium, calcium, magnesium, and phosphate levels. The results showed that the nocturnal systolic blood pressure

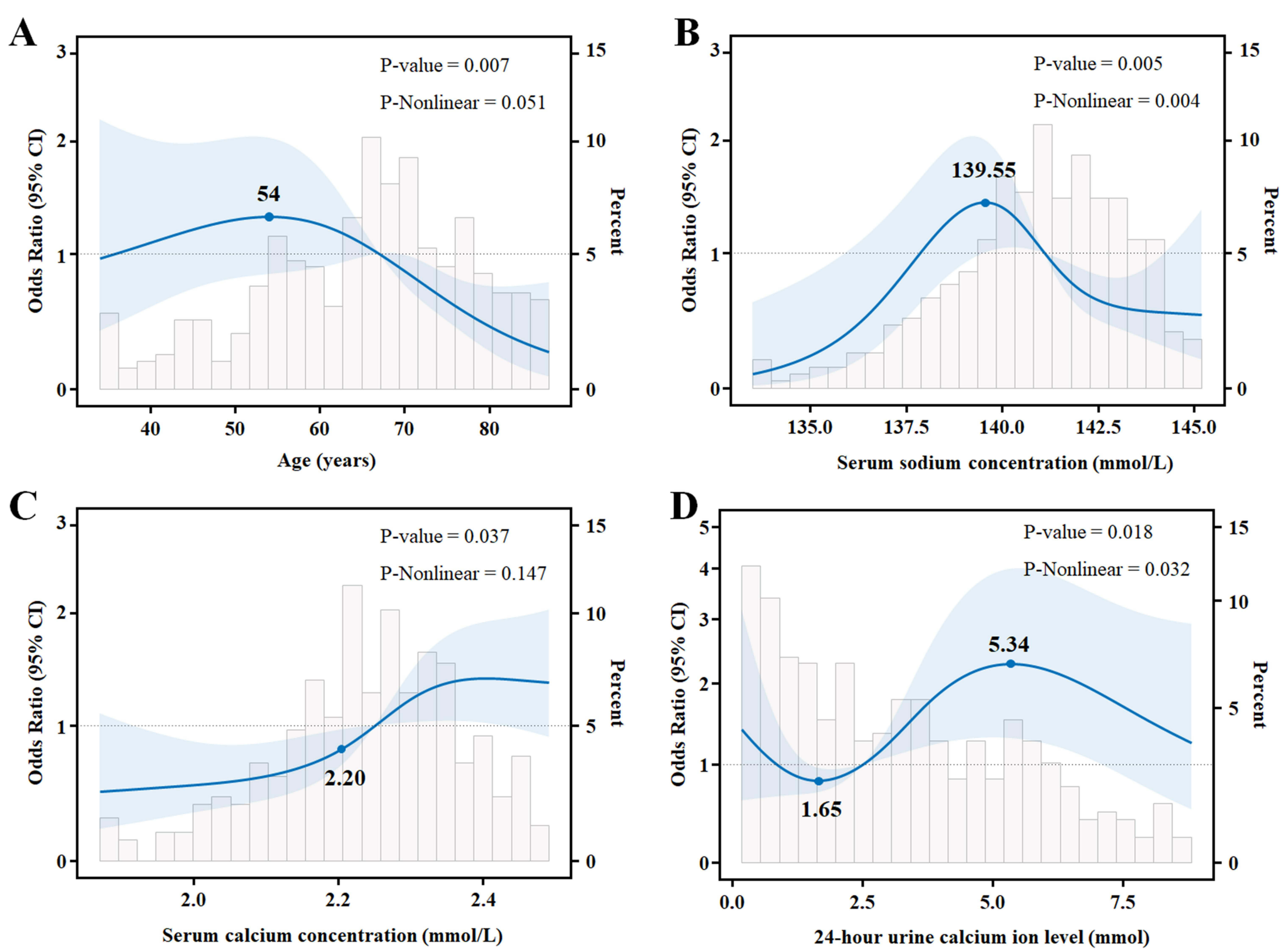

Figure 1 Relationship between dipper blood pressure pattern and various factors. (**A**) age, (**B**) serum sodium concentration, (**C**) serum calcium concentration, (**D**) 24-hour urine calcium ion level. The bold numerical indicate the most relevant turning point between two variables.

decline rate was associated with age, serum calcium ion concentration, and 24-hour urine calcium ion level (P < 0.001, P = 0.003, P = 0.015), while no significant associations were found with the other factors (P > 0.05).

The maximum nocturnal systolic blood pressure decline rate corresponded to an age of 57 years, a serum calcium ion concentration of 2.41 mmol/L, and a 24-hour urine calcium ion level of 5.47 mmol. The minimum nocturnal systolic blood pressure decline rate was observed at a 24-hour urine calcium ion level of 1.57 mmol. A serum calcium ion concentration greater than 2.20 mmol/L was significantly associated with an increased nocturnal systolic blood pressure decline rate. For more details, refer to Figure 2.

Relationship Between Nocturnal Diastolic Blood Pressure Decline Rate and Various Factors

A restricted cubic spline analysis was also conducted to assess the correlation between the nocturnal diastolic blood pressure decline rate and various factors, including age, gender, diabetes, serum sodium, calcium, and magnesium concentrations, as well as 24-hour urinary sodium, calcium, magnesium, and phosphate levels. The analysis indicated a significant correlation between the nocturnal diastolic blood pressure decline rate and age, serum sodium, calcium, and magnesium concentrations (P=0.032, P=0.039, P=0.001, P=0.041), with no significant correlation observed with other factors (P>0.05).

The maximum nocturnal diastolic blood pressure decline rate corresponded to serum sodium, calcium, and magnesium concentrations of 139.03 mmol/L, 2.42 mmol/L, and 0.95 mmol/L, respectively. A serum calcium concentration

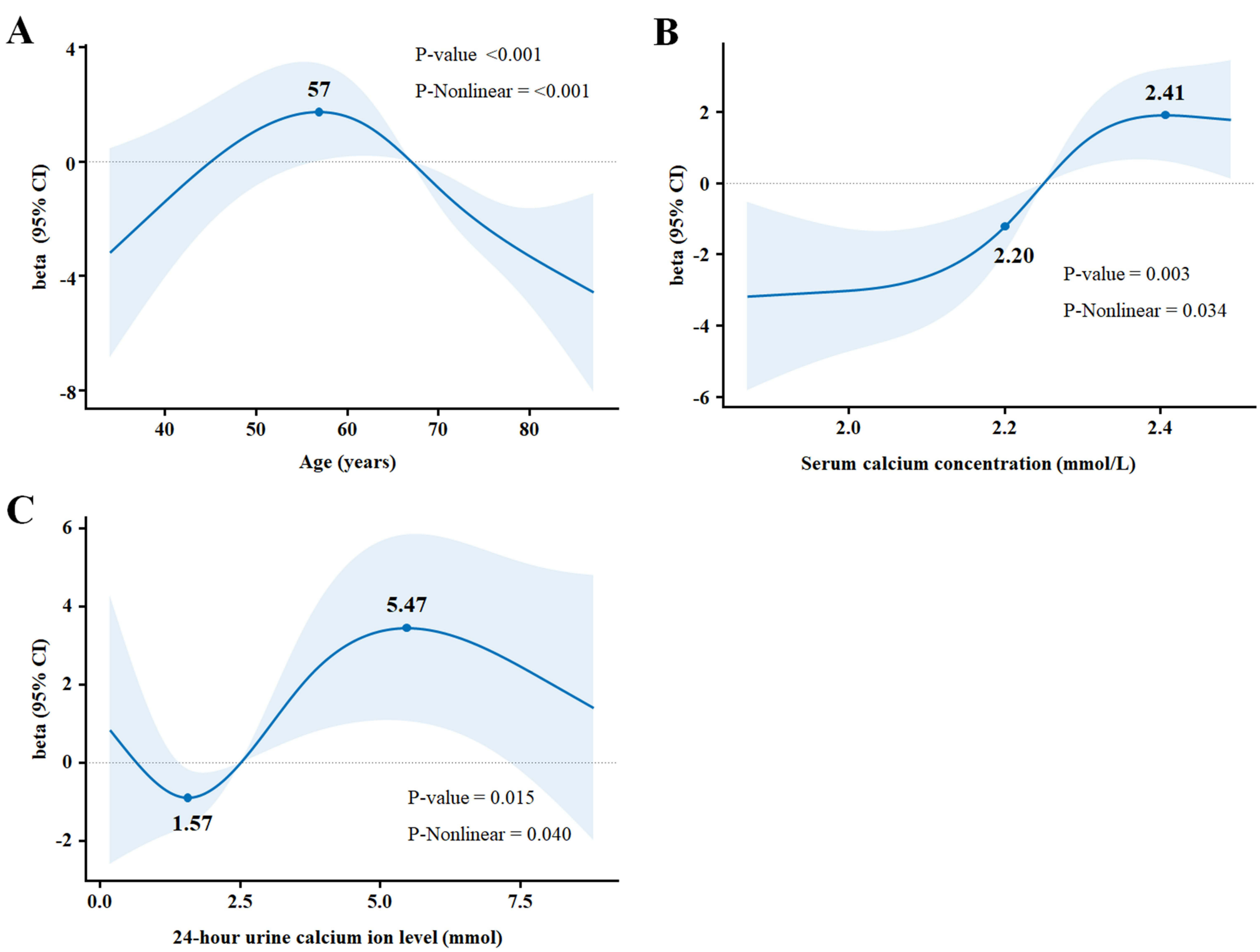

Figure 2 Relationship between nocturnal systolic blood pressure decline rate and various factors. (**A**) age, (**B**) serum calcium concentration, (**C**) 24-hour urine calcium ion level. The bold numerical indicate the most relevant turning point between two variables.

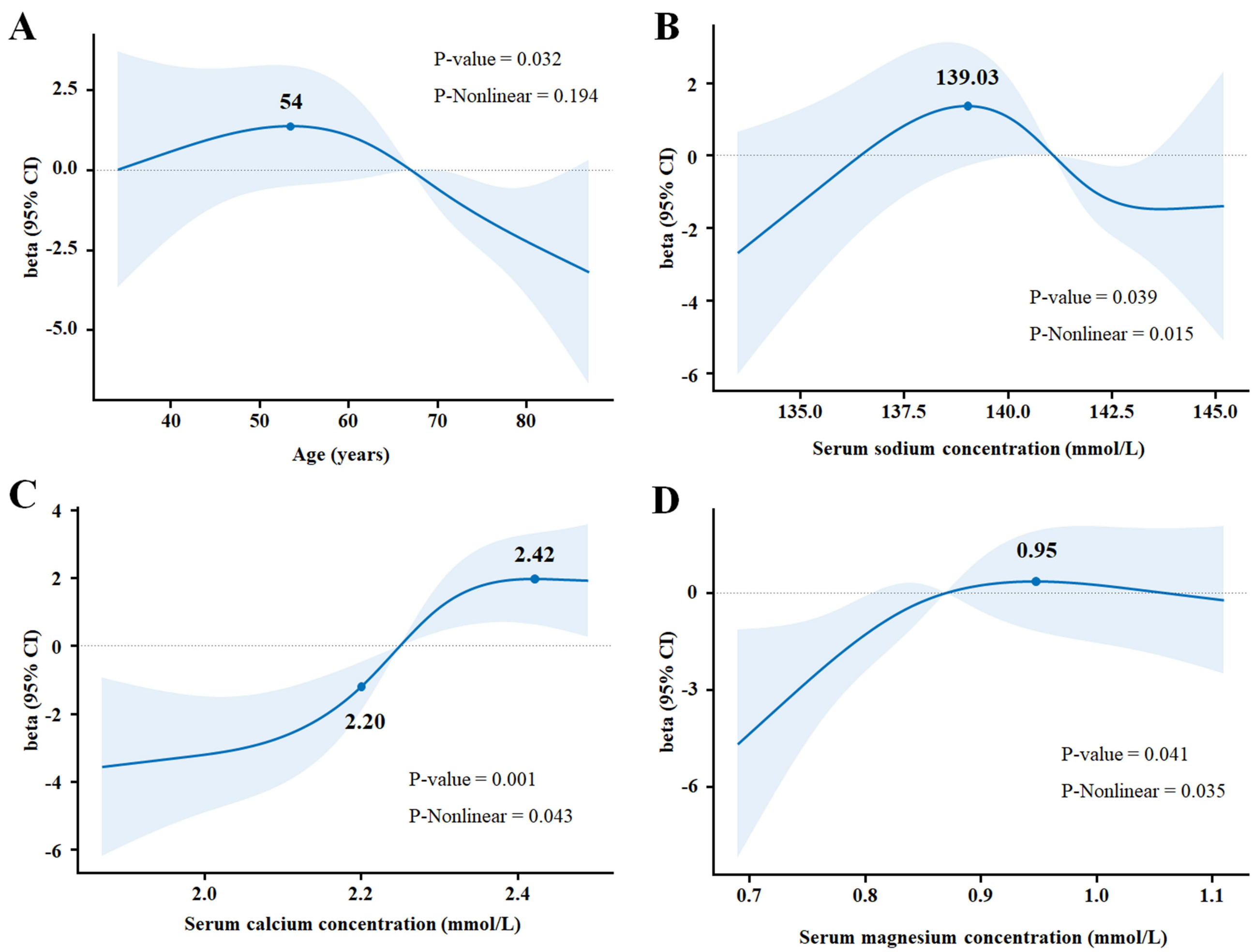

Figure 3 Relationship between nocturnal diastolic blood pressure decline rate and various factors. (**A**) age, (**B**) serum sodium concentration, (**C**) serum calcium concentration, (**D**) serum magnesium concentration.The bold numerical indicate the most relevant turning point between two variables.

greater than 2.20 mmol/L was significantly associated with an increased nocturnal diastolic blood pressure decline rate. Although age appeared to have a linear relationship with the nocturnal diastolic blood pressure decline rate (P for non-linearity =0.194), a trend plot revealed a distinct inflection point at the age of 54 years. See Figure 3 for details.

Discussion

The circadian rhythm of blood pressure, integral to cardiovascular homeostasis, is influenced by a complex interplay of hormonal and physiological factors, including melatonin, atrial natriuretic peptide, and the renin-angiotensin-aldosterone system.[16,17] This rhythm can be significantly altered by conditions such as obstructive sleep apnea, which disrupts the normal 24-hour blood pressure pattern and increases cardiovascular risk.[18] Our study revealed a significant association between advanced age and the non-dipper pattern of blood pressure, identifying age as an independent predictor of dipper blood pressure (Table 1 and 2). Restricted cubic spline (RCS) analysis further illuminated this relationship, indicating a linear association between age and dipper blood pressure with a notable inflection point at 54 years (Figure 1). Similarly, the nocturnal systolic and diastolic blood pressure decline rates showed significant age-related trends, peaking at 57 years and 54 years, respectively (Figures 2 and 3). These findings suggest a critical age threshold between 54 and 57 years, beyond which the likelihood of maintaining a dipper blood pressure pattern declines precipitously. These findings are corroborated by an Indian observational study of 27,472 patients, which documented a decrease in the prevalence of dipper blood pressure from 42.5% to 17.9% and a concurrent increase in reverse dipper blood pressure from 7.3% to 34.2% among individuals aged 30 to 80 years.[19] Research by Deng et al further supports this association, highlighting the independent impact of age on the amplitude of nocturnal blood pressure decline, particularly in elderly populations.[20] Collectively, these results underscore the age-related alterations in blood pressure rhythms and their clinical relevance in hypertension management.

Our study unveiled a significant positive correlation between calcium ions and dipper blood pressure patterns. Calcium, an abundant mineral in the human body, is crucial for maintaining skeletal structure, muscle contraction, vascular tone, blood clotting, nerve transmission, and energy metabolism.[21] In blood pressure regulation, calcium ions play a pivotal role by influencing ion channels on vascular smooth muscle cells, particularly the L-type voltage-dependent calcium channels, which are essential in modulating the tone of small arteries.[22] During hypertension, the function and expression of these ion channels may be altered, thereby affecting vascular tone. Although some studies have suggested that low-dose calcium intake may help lower blood pressure,[23,24] with more pronounced effects in younger individuals,[25] research on the correlation between calcium ion levels in blood and urine and dipper blood pressure patterns is relatively scarce. Our study found a correlation between serum calcium ions and dipper blood pressure (see Table 2), and both serum and urinary calcium levels were significantly associated with dipper blood pressure and the decline rates of nocturnal systolic and diastolic blood pressure. Higher levels of calcium ions in the blood and urine of hypertensive patients were associated with a greater likelihood of dipper blood pressure patterns (see Figures 1–3). Previous studies on the correlation between urinary calcium excretion and hypertension have found an inverse relationship between urinary calcium excretion and calcium concentration in renal interstitial fluid, suggesting that a decrease in calcium concentration in the renal cortical interstitial fluid may mediate renal vasoconstriction, thereby affecting blood pressure elevation and rhythm disruption.[26] Some research has indicated that compared to healthy individuals, hypertensive patients have higher urinary calcium excretion and parathyroid hormone levels, possibly due to intrinsic defects in renal calcium handling.[27] While the correlation and specific mechanisms between calcium ion concentrations in blood and urine and dipper blood pressure patterns are not yet fully understood, it is clear that calcium ion balance is crucial for maintaining overall blood pressure health. For hypertensive patients, monitoring and adjusting calcium intake and excretion may be an important direction for future research. We anticipate that further basic and clinical studies will explore this area to provide more insights into the role of calcium in hypertension management.

In this study, logistic regression analysis did not reveal a correlation between blood and urine sodium levels and dipper blood pressure profiles. Similarly, RCS analysis did not identify a relationship between 24-hour urine sodium levels and dipper blood pressure profiles. However, we found a significant association between serum sodium levels and dipper blood pressure profiles, as well as the nocturnal diastolic blood pressure fall rate, with inflection points at 139.55 and 139.03 mmol/L, respectively (see Figures 1 and 3). This suggests that hypertensive patients with a serum sodium level of 139 mmol/L have the highest likelihood of exhibiting a dipper blood pressure pattern. Some studies have indicated a "J-shaped" relationship between serum sodium concentration and primary cardiovascular events, with the lowest cardiovascular risk observed in individuals with serum sodium levels between 141 and 143 mmol/L.[28] Higher serum sodium concentrations are associated with an increased risk in hypertensive patients, and reducing salt intake can lower blood pressure in both hypertensive and normotensive individuals.[29] It is also recommended that hypertensive patients in China limit their daily sodium intake to less than 2g (less than 5g of sodium chloride).[1] Additionally, salt intake is correlated with blood pressure circadian rhythm. In salt-sensitive hypertensive rats, a high-salt diet leads to elevated blood pressure and non-dipper blood pressure profiles, which normalize upon a return to a regular salt diet, reverting to dipper blood pressure profiles.[30] Sodium overload promotes hypertension and disrupts circadian blood pressure rhythms through multiple, convergent pathophysiological pathways. High dietary Na^+ raises plasma osmolality, provoking arginine vasopressin release, extracellular fluid expansion, and sustained activation of the renin–angiotensin–aldosterone system; together these events potentiate vasoconstriction, vascular smooth-muscle hypertrophy, and a progressive rise in systemic vascular resistance.[31] Concurrently, excess Na^+ amplifies central sympathetic outflow via up-regulation of hypothalamic prolyl endopeptidase, accelerating norepinephrine release.[32] Furthermore, a high-sodium milieu directly impairs endothelial function by attenuating endothelial nitric-oxide synthase activity, diminishing nitric-oxide bioavailability, and triggering reactive oxygen species formation, thereby intensifying oxidative stress and blunting endothelium-dependent vasodilation.[33] The cumulative impact of these mechanisms not only elevates baseline blood pressure but also desynchronizes central and peripheral circadian clocks, driving the transition from a physiological nocturnal-dip pattern to non-dipping or reverse-dipping hypertension. So, it is evident that sodium is closely related to blood pressure and its circadian rhythm. The 24-hour urine sodium level is a more reliable indicator of salt intake.[34] Previous studies have found that individuals with dipper blood pressure profiles have lower 24-hour urine sodium levels compared to those with non-dipper profiles.[35] However, our results differ slightly from those of other scholars, possibly due to the single-center nature of our study, along with a smaller sample size and older age group.

In our study, we did not find a correlation between magnesium ions and dipper blood pressure profiles or the nocturnal systolic blood pressure fall rate. However, there was a certain correlation between serum magnesium levels and the nocturnal diastolic blood pressure fall rate, with an inflection point at 0.95 mmol/L (see Figure 3), suggesting that magnesium ions may have some association with blood pressure circadian rhythm. Magnesium is the second most abundant intracellular cation in the human body and is widely involved in various physiological functions, affecting vascular endothelial cells, vascular inflammation, and oxidative stress. Insufficient magnesium intake may be associated with an increased risk of hypertension,[36] while higher serum magnesium levels are independently associated with a lower risk of cardiovascular events.[37] A cross-sectional study of 443 children aged 6–9 years in Guangzhou, China, found that higher levels of serum magnesium and calcium were negatively correlated with blood pressure.[38] Although numerous studies have demonstrated a close relationship between lower levels of serum magnesium and the occurrence and progression of hypertension,[39] and dietary magnesium supplementation has been shown to have a certain antihypertensive effect,[40] research on the relationship between magnesium ions and blood pressure circadian rhythm is still relatively scarce. Magnesium ions may influence the nocturnal diastolic blood pressure fall rate by acting as a calcium antagonist, affecting the renin-angiotensin-aldosterone system, improving endothelial function, influencing vascular remodeling and stiffness, and regulating the release of catecholamines.[41] In the analysis of the correlation between phosphate ions and dipper blood pressure profiles, although patients in the dipper group had higher 24-hour urinary phosphate levels than those in the non-dipper group, no other statistically significant differences were found. This suggests that the correlation between phosphate ions and blood pressure circadian rhythm may require further exploration.

Non-dipper or reverse-dipper blood pressure patterns are associated with an increased risk of cardiovascular events and renal failure.[42] Aggressive blood pressure control, particularly optimized antihypertensive therapy, can yield greater benefits for hypertensive patients.[1] In our study, we delved into the correlation between serum levels of sodium, calcium, magnesium, and phosphate and the dipper pattern of blood pressure among hypertensive patients. Our findings underscore a significant association between these electrolytes and the dipper blood pressure profile, suggesting that the monitoring and modulation of these ions' intake and excretion could represent a promising avenue for intervention in hypertension management. We observed that the likelihood of maintaining a dipper blood pressure pattern diminishes with advancing age, indicating a need for more nuanced assessment and vigilant monitoring of blood pressure circadian rhythms in the elderly hypertensive population. Furthermore, our analysis revealed an independent negative correlation between alpha-blockers and the dipper blood pressure pattern (as detailed in Table 2), which implies that such pharmacological agents may not be optimal for preserving the normal circadian rhythm of blood pressure in hypertensive patients. This hypothesis warrants further investigation through additional clinical studies. The clinical implications of our study are substantial. They suggest that personalized blood pressure management, coupled with strategic lifestyle modifications—such as sodium restriction and the optimization of calcium, phosphate, and magnesium intake—could enhance the control of hypertension and its circadian variations. This, in turn, may contribute to a reduction in the risk of cardiovascular events. The application of ambulatory blood pressure monitoring is also highlighted as a valuable tool for evaluating blood pressure rhythms, offering crucial insights for the diagnosis and therapeutic management of hypertension.

Limitations

As a single-center cross-sectional study, our conclusions may be subject to certain biases that could limit the generalizability of our findings. The study population was skewed towards older age groups and had an imbalanced gender ratio, which may have influenced the analysis of the correlation between ion levels and blood pressure rhythm. We did not fully account for patients' lifestyle and dietary habits, factors that could impact blood pressure rhythm and ion levels. The cross-sectional design of our study also restricts our ability to establish causality. Future research should employ multicenter, large-sample, prospective cohort study designs to enhance the universality and reliability of the findings and to explore additional potential biomarkers and interventions. Through these approaches, we can gain a more comprehensive understanding of the regulatory mechanisms of blood pressure rhythm and provide more effective treatment strategies for hypertensive patients. Future investigations should also aim to elucidate the underlying mechanisms by which these electrolyte levels influence blood pressure circadian rhythms and to evaluate the efficacy of these management approaches across diverse patient demographics.

Conclusion

In conclusion, our study revealed significant associations between serum levels of sodium, magnesium, calcium, and other ions with dipper blood pressure patterns, suggesting that these ions in blood and urine may serve as potential predictors or early warning indicators for dipper blood pressure. Maintaining these ions within certain ranges may also aid in preserving the dipper pattern. Our research substantiates the critical role of integrating blood pressure rhythm and electrolyte homeostasis into hypertension management strategies, potentially improving patient outcomes.

Data Sharing Statement

Data will be made available on request from the corresponding author, Yi-Hong Wei.

Ethics Approval and Consent to Participate

This study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of Longhua Hospital affiliated to Shanghai University of Traditional Chinese Medicine.

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Disclosure

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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