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Early and persistent blood pressure dysregulation in individuals with subacute motor incomplete spinal cord injury

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ABSTRACT

Context: Blood pressure (BP) dysregulation after spinal cord injury (SCI) may disrupt circadian BP rhythms, including absent nocturnal dipping, high BP variability, and hypertension. These disturbances are independent predictors of cardiovascular disease, yet evidence in older adults with subacute motor incomplete SCI is limited.
Objective: To characterize nocturnal dipping status, BP variability, and daytime and nighttime hypertension at admission to inpatient rehabilitation, and to assess changes during rehabilitation.
Design:: Observational cohort study.
Setting: Primary inpatient rehabilitation center.
Participants: Individuals with motor incomplete SCI who completed 24-hour ambulatory BP monitoring shortly after admission and before discharge.
Interventions: Not applicable.
Outcome measures: Nocturnal dipping (% reduction from nighttime to daytime systolic BP), BP variability, and hypertension defined using general population thresholds.
Results: Participants with motor incomplete SCI were included (n = 34, mean age 61 years, 82% male, 44% cervical injury). At admission, 82% were classified as non-dippers or reverse dippers. High BP variability was present in 59% for systolic BP and 29% for diastolic BP. Hypertension occurred in 21% during daytime and 59% during nighttime. All but one participant exhibited at least one BP-related risk factor. No changes were observed in dipping status, BP variability, and mean BP levels between admission and discharge (all $p > 0.05$).
Conclusion: Marked BP dysregulation is evident early after motor incomplete SCI, including absent nocturnal dipping, high BP variability, and nocturnal hypertension, despite daytime BP appearing within normal limits in most participants. These disturbances persisted throughout rehabilitation, indicating ongoing autonomic dysregulation that may contribute to long-term cardiovascular risk.

KEYWORDS
Ambulatory blood pressure monitoring; Circadian rhythm; Hypertension; Rehabilitation; Spinal cord injuries

Introduction

Cardiovascular disease (CVD) is one of the leading causes of mortality in the spinal cord injury (SCI) population (1, 2). Compared with the general population, individuals with SCI experience an earlier onset and higher prevalence of CVD (3). Disruptions in the autonomic nervous system following SCI can lead to abnormal blood pressure (BP) regulation, thereby contributing to the increased CVD risk in this population (4).

Nocturnal dipping, the physiological decline in BP during nighttime compared to daytime, occurs in approximately 84% of the able-bodied population (5). Absence of this dipping pattern is associated with hypertension-mediated organ damage such as impaired renal function, and increased cardiovascular morbidity and mortality (5–7). Importantly, absence of nocturnal dipping is considered an independent risk

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factor for CVD (6). Similarly, high BP variability and hypertension are also recognized as independent determinants of CVD, linked to mechanisms such as increased vascular injury (8–10).

In individuals with SCI, autonomic disturbances frequently alter the typical daily circadian BP rhythm, often resulting in the absence of nocturnal dipping, high BP variability, and hypertension, while hypotension may also occur as part of this broader BP dysregulation (11, 12). These disturbances may compromise rapid BP adjustments, thereby increasing variability and exacerbating cardiovascular risk. Although nocturnal dipping, variability, and hypertension have been described in this population, most studies have mainly focused on younger individuals with motor complete and traumatic SCI (11, 13–21).

Due to the epidemiologic changes, this group no longer represents the current SCI population. In fact, the current population predominantly comprises older individuals with motor incomplete cervical SCI, and is characterized by a high prevalence of CVD history and other comorbidities (22–26). Because motor incomplete SCI involves partial preservation of motor and autonomic pathways, BP regulation may differ from that observed in individuals with motor complete injuries. Nevertheless, there is limited information on the extent of autonomic dysfunction and its impact on circadian BP regulation in individuals with motor incomplete SCI (27).

Furthermore, little is known about BP regulation during the subacute rehabilitation phase, and whether these patterns change during this period (28, 29). This period is characterized by ongoing neurological recovery, increasing physical activity, and medication changes, all of which may affect BP regulation over time. This insight is clinically relevant, as this phase may represent a critical window for implementing preventive strategies.

Therefore, the aim of this study was to characterize circadian BP rhythm and BP-related risk factors at admission of the subacute inpatient rehabilitation period in individuals with motor incomplete SCI. Specifically, we focused on nocturnal dipping, BP variability, and daytime and nighttime hypertension. We also examined whether dipping ratios, BP variability, and mean BP levels changed throughout the rehabilitation period. We hypothesized that individuals with SCI would demonstrate reduced nocturnal dipping, high BP variability, and frequent hypertension, with these BP abnormalities becoming more pronounced during inpatient rehabilitation.

Methods

Study design and participants

This observational cohort study was conducted at the Sint Maartenskliniek (Nijmegen, the Netherlands). Continuous 24-hour BP measurements were scheduled at two predefined time points for research purposes to evaluate potential changes in BP regulation during inpatient rehabilitation. The first assessment was conducted after participants completed the initial two-week period after admission. This period allowed participants to adjust to the rehabilitation setting and ensured that the first study assessment was performed after the initial admission phase, during which participants typically undergo multiple clinical evaluations and rehabilitation planning activities. The second measurement was typically planned about two weeks before discharge, primarily for practical reasons. If the total rehabilitation period was shorter than one month, the second measurement was not performed. Data were collected between April 2023 and March 2024. This study received WMO (Medical Research Involving Human Subject Act) exemption (2023-16294) and was approved by the local ethics committee. Eligible individuals gave written informed consent prior to the study procedures.

Eligible participants were adults (≥18 years) with motor incomplete SCI of any neurological level, classified as grade C or D according to the American Spinal Injury Association Impairment Scale (AIS) (30). Furthermore, participants were recruited during the subacute phase (<six months post-injury) of the inpatient rehabilitation period and were required to actively participate in the rehabilitation program. Exclusion criteria comprised inability to provide informed consent or presence of a language barrier.

Participant characteristics

Demographic information (sex, age, weight, height) was extracted from the electronic patient record, and body mass index (BMI) was calculated as weight divided by height squared (kg/m^2). BMI was categorized using SCI-specific cutoffs: recommended (<22 kg/m^2), overweight (22-24.9 kg/m^2), and obese (≥25 kg/m^2)

(31). Injury-related characteristics were also obtained from the patient record and included neurological level of injury and completeness of SCI at admission, etiology, and time since injury. Lesion level and completeness were determined using the International Standards for Neurological Classification of SCI (ISNCSCI) (30). Cardiometabolic risk factors, including history of CVD, diabetes, cholesterol levels, and relevant medication use were obtained from the electronic medical record. In addition, participants self-reported their smoking status.

Ambulatory blood pressure monitoring

During the assessments, participants underwent 24-hour ambulatory BP assessment using an oscillometric device (Mobil-O-Graph NG, IEM GmbH, Aachen, Germany). This device recorded systolic BP (SBP) and diastolic BP (DBP) readings at 20-minute intervals during daytime and at 60-minute intervals at night.

The arm with the highest BP reading was selected for the monitoring period, unless contraindicated by factors such as glucose monitoring devices, pain, or muscle spasms, which can increase the likelihood of measurement errors. In such cases, the contralateral arm was used. Participants were instructed to maintain usual medication schedules and daily activities, as medication relevant to CVD risk and physical activity are known to be important confounders in BP regulation (32). Furthermore, participants were asked to complete a diary documenting their sleep onset and wake-up times, which was consequently used to individually define nighttime periods for BP and physical activity analysis. To objectively quantify physical activity during BP measurements, given its role as a potential confounder, participants wore a validated accelerometer (ActivPAL^{TM} micro, PAL Technologies, Glasgow, UK) attached to the right upper leg (32). This small device ($25 \times 45 \times 75$ mm) was sealed with a nitrile sleeve and transparent tape for waterproof protection and attached using hypoallergenic tape. The accelerometer accurately distinguished between periods of sedentary behavior, standing, and stepping based on posture (33). Raw accelerometry data were subsequently processed using PALanalysis software v8 (PAL Technologies, Glasgow, UK), converted with the VANE algorithm v0.1, and analyzed using R version 4.4.2 (R Core Team, 2025, Vienna, Austria) to quantify the duration of physical activity (standing and stepping) over the 24-hour measurement period.

Circadian blood pressure rhythm

Raw ambulatory BP data were imported into R version 4.4.2 (R Core Team, 2025, Vienna, Austria) for processing and analysis. Recordings were reviewed for completeness and consistency before analysis. Daytime and nighttime periods were defined individually based on participants' diaries. When sleep times were missing at discharge, the sleep time recorded at admission was used to estimate sleep duration. After excluding the initial BP reading taken prior to the 24-hour measurement and other readings not intended for analysis, the remaining data were aggregated into hourly means to describe circadian BP rhythm.

Blood pressure related risk factors

Ambulatory BP outcomes, including nocturnal dipping status and variability metrics, were calculated using the *bp* package in R version 4.4.2 (R Core Team, 2025, Vienna, Austria). Our primary outcome, nocturnal dipping, was assessed using the night-to-day SBP ratio (11). Nocturnal dipping was calculated as the percentage of nighttime SBP relative to daytime. Participants were subsequently classified as normal dippers ($\leq$90%), non-dippers (90–100%), or reverse dippers (>100%) (10). As a secondary outcome, BP variability during daytime and nighttime was assessed. Average Real Variability (ARV) was considered as the primary metric, as it represents the mean of absolute differences between consecutive BP measurements, and is recognized for its prognostic significance in 24-hour ambulatory monitoring (34). Previous studies have classified high ARV of 24-hour ambulatory BP as $\geq$9.3 mmHg SBP and $\geq$8.8 mmHg for DBP (35). To provide a normalized index of variability relative to the mean, the Coefficient of Variation (CoV) was additionally used. The CoV was calculated as the standard deviation divided by the mean BP and no clinical thresholds were applied in this study. The third outcome was defined using conventional thresholds: daytime hypertension as a mean awake SBP $\geq$135 mmHg and/or DBP $\geq$85 mmHg, and nighttime hypertension as a mean asleep SBP $\geq$120 mmHg and/or DBP $\geq$70 mmHg (36).

Statistical analysis

For our primary analysis at admission, we used descriptive statistics to characterize the circadian BP rhythm and summarize four BP-related risk factors: nocturnal dipping, BP variability, and daytime and nighttime hypertension. In addition, we assessed at the individual level whether each participant met at least one of these risk criteria. Continuous variables were presented as mean (SD), and categorical variables as counts and percentages.

To address our second research question, we examined changes in nocturnal dipping ratios, BP variability (day and night), mean BP levels, and potential BP confounders (medication use and physical activity) across the inpatient rehabilitation period. Continuous variables were analyzed using the Wilcoxon signed-rank test, and categorical variables using McNemar's test. The threshold for statistical significance was set at $p < 0.05$, and all analyses were also performed using R version 4.4.2 (R Core Team, 2025, Vienna, Austria).

Results

Participant characteristics

Among the 63 eligible individuals, 37 (59%) provided informed consent, and 34 participants were included in the study. A schematic representation of the participant inclusion flow is presented in Fig. 1.

Table 1 summarizes baseline characteristics of participants at the first assessment during subacute inpatient rehabilitation. The cohort was predominantly male (82%). Based on SCI-specific cutoffs, 53% were classified as obese, 44% as overweight, and 3% within the recommended range. Most participants were classified as AIS D (76%) and had a non-traumatic etiology of SCI (71%). Half of the participants had a documented history of CVD, and 47% were receiving antihypertensive therapy. No participants were using medications to increase BP.

Circadian blood pressure rhythm at admission

Mean (SD) BP values during the 24-hour measurement period at admission were 125 (12) mmHg for SBP and 77 (8) mmHg for DBP. Across the measurement period, SBP ranged from 62 to 217 mmHg and DBP from 40 to 121 mmHg. An overview of hourly mean BP values for all participants at admission is provided in Fig. 2.

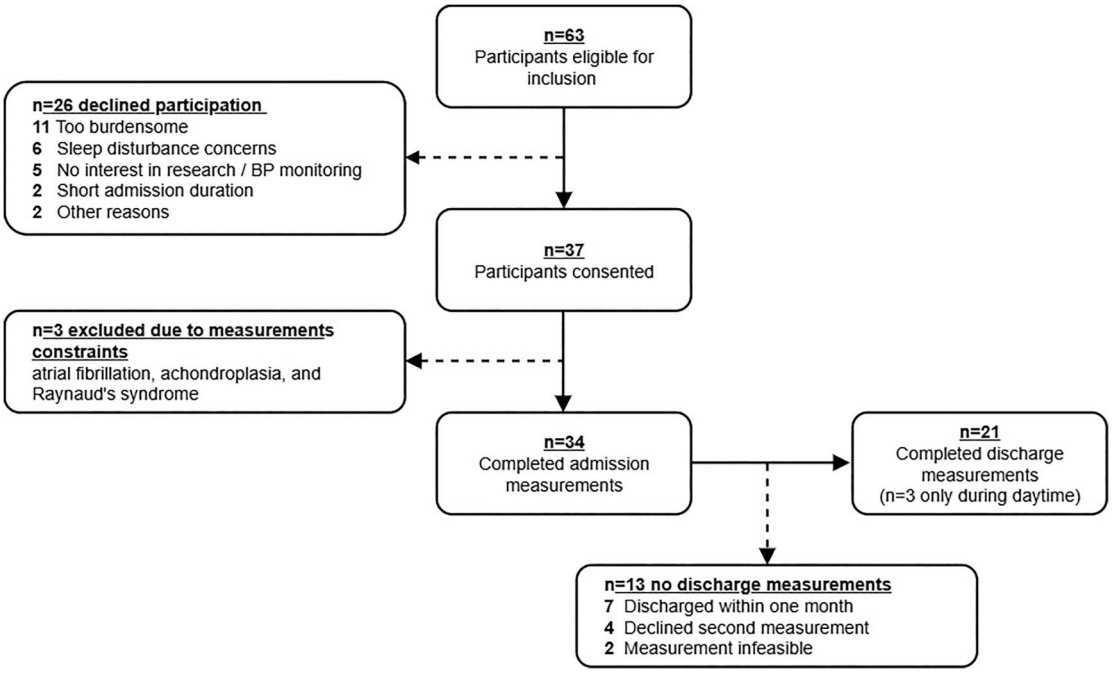

Figure 1. Participant inclusion and measurement flow. Abbreviation: BP = blood pressure.

Table 1. Baseline characteristics of participants at admission ($n = 34$).

Demographic characteristics	Mean (SD) or *n (%)*
Sex, *n (%)*	
Male	*28 (82)*
Female	*6 (18)*
Age (years), mean (SD)	61 (14)
Body mass index (kg/m^2), mean (SD)	27.3 (5.1)
SCI characteristics	
Neurological level of injury, *n (%)*	
Cervical (C1 – C7)	*15 (44)*
Thoracic (T1 – T12)	*12 (35)*
Lumbar (L1 – L5)	*7 (21)*
Lesion level, *n (%)*	
High (≥T6)	*19 (56)*
Low (<T6)	*15 (44)*
AIS classification at admission, *n (%)*	
AIS C	*8 (24)*
AIS D	*26 (76)*
Etiology of SCI, *n (%)*	
Traumatic	*10 (29)*
Non-traumatic	*24 (71)*
Time since injury (days), mean (SD)	51 (17)
Inpatient rehabilitation length of stay (days), mean (SD)	66 (36)
Cardiometabolic risk factors	
History of cardiovascular disease, *n (%)* †	*17 (50)*
Hypertension	*8 (47)*
Aortic diseases	*2 (12)*
Cardiac arrhythmias	*2 (12)*
Cardiomyopathy	*2 (12)*
Coagulation disorders	*2 (12)*
Inflammatory heart disease	*2 (12)*
Cerebrovascular disease	*1 (6)*
Inflammatory vascular disease	*1 (6)*
Valvular disease	*1 (6)*
Diabetes Mellitus, *n (%)*	*6 (18)*
Type 1	*1 (17)*
Type 2	*5 (83)*
Total cholesterol (mmol/L), mean (SD) ‡	4.3 (1.1)
Anti-hypertensive medication, *n (%)* †	*16 (47)*
Beta-blockers	*8 (50)*
Calcium antagonists	*6 (38)*
ACE-inhibitors	*5 (31)*
Diuretics	*4 (25)*
Angiotensin blockers	*3 (19)*
Alfa-blocker	*2 (13)*
Smoking history	
Current or former smoker, *n (%)*	*24 (71)*
Packyears, mean (SD)	17 (17)

†Multiple conditions or medication categories can exist within one participant; therefore, total percentages can exceed 100%.
‡n = 33.
Continuous variables are presented as mean (SD) and categorical variables as n (%).
Abbreviations: ACE = angiotensin-converting enzyme; AIS = American Spinal Injury Association Impairment Scale; SCI = spinal cord injury.

Blood pressure related risk factors at admission

At admission, 18% of participants were classified as dippers, 44% as non-dippers, and 38% as reverse dippers (Fig. 3A). A substantial proportion exceeded the established high ARV thresholds, with 59% above the threshold for SBP and 29% for DBP (Fig. 3B). The CoV for daytime SBP was 10% (SD 2) and for DBP 11% (SD 3). During nighttime, CoV was 8% (SD 3) for SBP and 11% (SD 4) for DBP. Daytime hypertension was observed in 21% of participants, while nighttime hypertension was present in 59% (Figs. 3C and D).

An overview of the four BP-related risk factors (daytime hypertension, abnormal nocturnal dipping, high ARV, and nighttime hypertension) on the individual level demonstrated that with the exception of one participant, everyone had at least one BP-related risk factor (Table 2). Among those with daytime hypertension, every participant had at least one additional BP-related risk factor. Notably, 16 participants without daytime hypertension also presented with two or more risk factors.

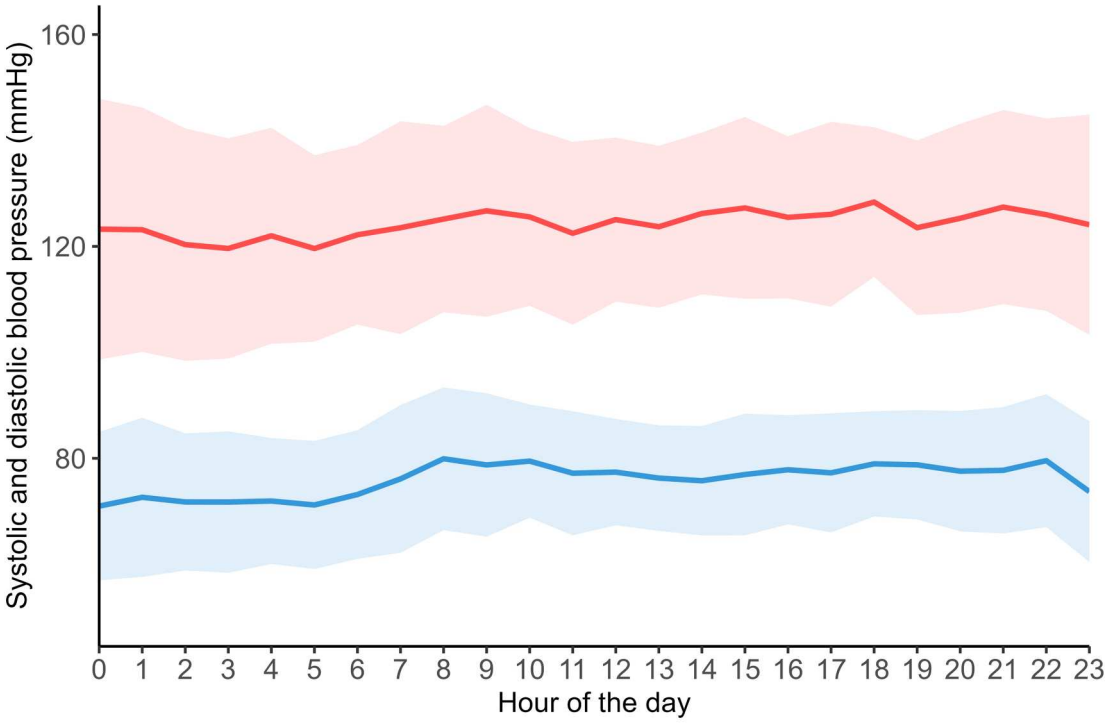

Figure 2. Hourly means of systolic and diastolic blood pressure at admission. The red panel shows mean hourly systolic blood pressure and the blue panel shows mean hourly diastolic blood pressure at admission over the 24-hour measurement period. Shaded areas indicate the SD.

Changes in blood pressure regulation during inpatient rehabilitation

Of the included participants, 62% completed the second measurement before discharge. Table 3 summarizes data from participants with measurements at both admission and discharge. Baseline characteristics of the participants who did not complete the measurements at discharge, did not differ from those of participants who completed both measurements, except for inpatient rehabilitation length of stay ($p = 0.001$, Supplementary Table S1). Dipping ratios remained unchanged between admission and discharge ($p = 0.862$). Similarly, no changes were observed during inpatient rehabilitation for BP variability (CoV and ARV) or for average daytime and nighttime BP values (Table 3).

Changes in confounding variables during inpatient rehabilitation

All participants using anti-hypertensive medication ($n = 16$) continued the same medication throughout the inpatient rehabilitation period. Paired physical activity data, calculated as the combined duration of standing and stepping time, were available for 16 participants. Mean physical activity time was 51 (SD 73) minutes at admission, and 78 (SD 88) minutes at discharge, with no significant change ($p = 0.159$).

Discussion

This study evaluated circadian BP regulation in individuals with motor incomplete SCI during inpatient rehabilitation. The first aim was to assess the presence of nocturnal dipping, BP variability, and hypertension at admission. The second aim was to examine whether these outcomes changed during the two-month inpatient rehabilitation period. Despite normal daytime mean BP values at admission in most participants (79%), the majority of the population demonstrated: (1) absence of nocturnal dipping (82%), (2) pronounced BP variability, particularly in SBP ARV (59%), and (3) nighttime hypertension (59%). Importantly, no significant changes in these outcomes were detected over the inpatient rehabilitation period. These findings indicate that impaired circadian BP regulation, reflected by absence of nocturnal dipping, high SBP variability, and

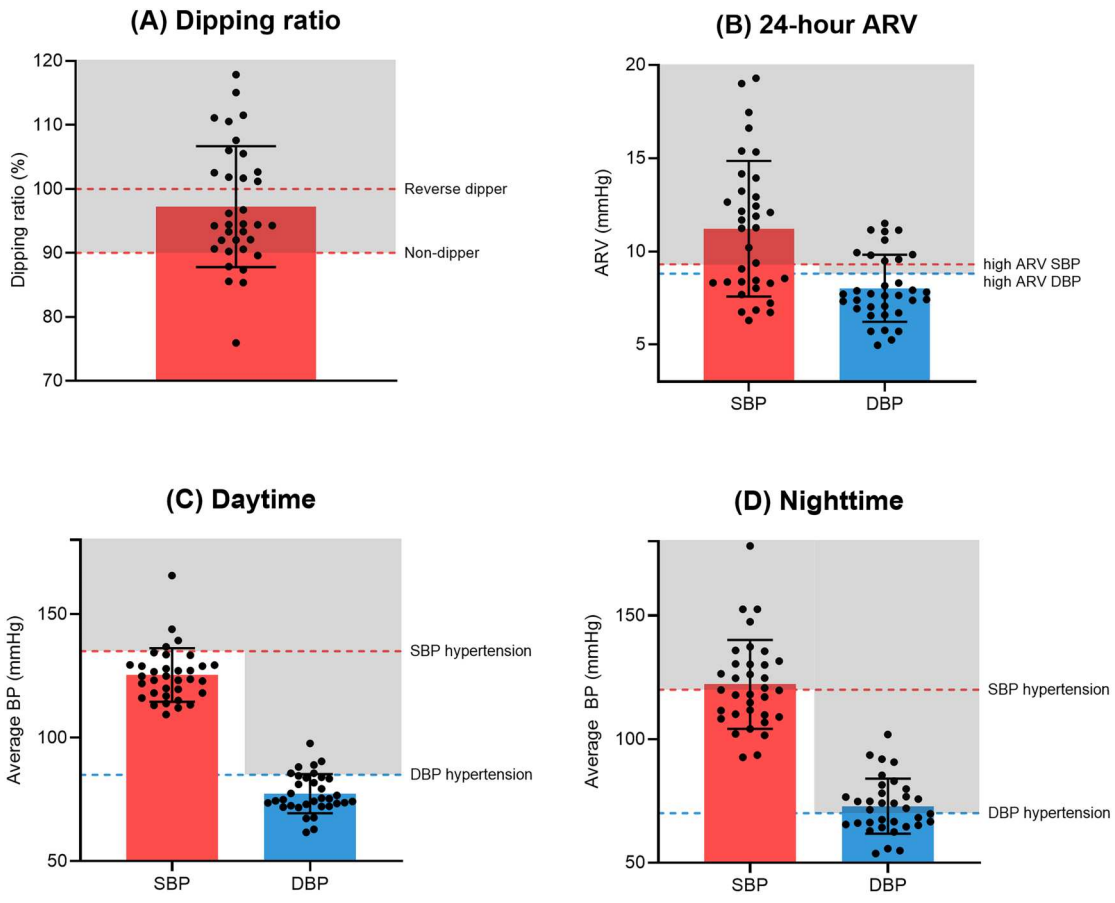

Figure 3. Blood pressure patterns and variability with thresholds at admission. Individual participant data are shown as black dots, with group means and SD indicated. Panel A shows nocturnal dipping ratios; Panel B illustrates the 24-hour average real variability (ARV) for systolic blood pressure (SBP) and diastolic blood pressure (DBP); Panels C and D present daytime and nighttime average blood pressure (BP) values, respectively. Gray shaded areas represent ranges associated with increased cardiovascular risk. Literature-based cutoff values for dipping, variability, and hypertension are indicated by the red dotted lines (SBP) and blue dotted lines (DBP).

frequent nighttime hypertension, is present soon after injury. As all these factors are independently associated with elevated cardiovascular risk, our results underscore the importance of early preventive strategies to mitigate CVD burden in this population.

In line with our hypothesis, we found a high prevalence of abnormal dipping patterns at admission, with a remarkably high proportion of participants (82%) classified as non-dippers or reverse dippers. This is substantially higher than in the general population, where abnormal dipping patterns typically occurs in ~16% of the population (5). This prevalence even exceeds rates reported in other high-risk groups such as individuals with chronic kidney disease and diabetes (≈50% to ≈70%) (10). Interestingly, the high prevalence of abnormal dipping patterns soon following injury aligns with prior observations in individuals with chronic SCI, where such patterns have been reported in up to 90% of cases (11, 14). In marked contrast to these previous studies, a unique element of our study was the early assessment following injury, which was on average 51 days post-injury. This suggests that non-dipping patterns emerges soon after injury and persists over time, a notion supported by our observation that dipping ratios did not change across the two-month period of inpatient hospitalization.

We observed high SBP variability in 59% of participants at admission, which remained unchanged during rehabilitation. In line with the high prevalence of absent nocturnal dipping, ARV values for SBP typically exceeded those reported in normotensive individuals and approached the ranges reported for DBP (35). Moreover, ARV values for SBP and DBP in our participants with motor incomplete SCI were comparable to those with untreated hypertension (35). Our findings for ARV, obtained in the subacute phase, align

Table 2. Individual blood pressure risk profile.

Participant ID	Daytime hypertension	Abnormal nocturnal dipping	High ARV SBP/DBP	Nighttime hypertension	Overall BP-risk
1		X	X	X	
2		X	X		
3					
4	X	X		X	
5		X			
6		X		X	
7		X			
8			X		
9		X	X		
10		X			
11	X	X		X	
12		X		X	
13	X	X	X	X	
14			X		
15		X	X	X	
16		X	X	X	
17			X		
18		X		X	
19			X		
20		X			
21		X		X	
22	X			X	
23		X			
24		X	X	X	
25		X	X	X	
26	X	X	X	X	
27		X	X	X	
28		X	X	X	
29		X	X	X	
30		X			
31	X	X	X	X	
32		X	X	X	
33	X	X	X	X	
34		X	X		
Total abnormal, n (%)	**7 (21)**	**28 (82)**	**20 (59)**	**20 (59)**	

Colors indicate the cumulative number of blood pressure related risk factors per participant.

Abbreviations: ARV = average real variability; BP = blood pressure; DBP = diastolic blood pressure; SBP = systolic blood pressure.

Color	Risk factor count
	No BP-related risk factors
	One BP-related risk factor
	Two BP-related risk factors
	Three BP-related risk factors
	Four BP-related risk factors

Table 3. Blood pressure patterns and variability measured at admission and discharge ($n = 21$).

	Admission n = 21		Discharge n = 21		*p* value	
	SBP	DBP	SBP	DBP	SBP	DBP
Nocturnal dipping						
Dipping ratio, mean (SD) †	96.7 (10.2)		95.3 (12.7)		0.862	
Blood pressure variability						
CoV daytime (%), mean (SD)	11 (2)	12 (3)	10 (3)	12 (4)	0.465	0.627
CoV nighttime (%), mean (SD) †	8 (3)	11 (4)	10 (4)	12 (6)	0.384	0.965
ARV daytime (mmHg), mean (SD)	13 (4)	9 (3)	12 (6)	9 (4)	0.385	0.578
ARV nighttime (mmHg), mean (SD) †	11 (6)	8 (4)	11 (7)	8 (4)	0.571	0.705
Average blood pressure						
Daytime (mmHg), mean (SD)	127 (14)	77 (9)	125 (13)	78 (9)	0.384	0.348
Nighttime (mmHg), mean (SD) †	123 (10)	71 (8)	118 (12)	70 (8)	0.360	0.695

Analyses include participants with complete measurements at both time points (n = 21), except for dipping ratio and nighttime outcomes (n = 18). Continuous variables are presented as mean (SD).

† n = 18.

Abbreviations: ARV = average real variability; CoV = coefficient of variation; DB*P* = diastolic blood pressure; SB*P* = systolic blood pressure

closely with observations in younger and chronic SCI cohorts (13, 19, 21). For example, Hill *et al.* reported that individuals with predominantly motor complete injuries and higher neurological levels exhibited greater SBP variability compared to the non-SCI population (19). While we reported similar patterns of high SBP variability, an important difference from this previous study is that we included participants with a motor incomplete lesion across all neurological levels of injury. This suggests that abnormal BP regulation may not be determined solely by neurological level or motor completeness of the injury (37). However, the relatively small sample size did not allow for meaningful subgroup analyses according to neurological level or injury completeness. Taken together, these findings suggest that high BP variability is an early and persistent feature of SCI, irrespective of time since injury.

Abnormalities were also observed in average nighttime BP, with 59% of participants meeting conventional criteria for nighttime hypertension at admission, compared to 13-23% in the general population (10). In contrast, the prevalence of daytime hypertension in our cohort (21%) was markedly lower than that reported for the general population (38). Notably, participants without daytime hypertension often exhibited other forms of abnormal BP regulation, characterized by absent nocturnal dipping, high BP variability, or nighttime hypertension. The presence of these factors is not necessarily interrelated, as absent nocturnal dipping, high BP variability, and nighttime hypertension each hold prognostic value for future CVD, independent of daytime hypertension. In fact, reduced nocturnal BP decline is a strong predictor of cardiovascular mortality, with reverse dipping conferring an even greater risk, while high SBP variability is an established predictor of CVD in the SCI population (6, 21, 39). Furthermore, nocturnal hypertension is closely linked to adverse cardiovascular events and organ damage (40). Therefore, an important observation in our study was that all but one participant exhibited at least one of the four abnormal BP outcomes (Table 2), each representing an independent cardiovascular risk factor.

A unique element in our study was the re-evaluation of BP-related outcomes before discharge. Contrary to our expectations, we found no changes in BP regulation (*i.e.* nocturnal dipping ratio, BP variability, and mean BP levels) between admission and discharge. This lack of change highlights that these disturbances are already present soon after injury, and remain stable throughout rehabilitation. The persistence of impaired BP regulation in individuals with motor incomplete SCI, combined with the prognostic value of these outcomes, highlights the importance of early detection during routine clinical assessments. Conventional daytime BP measurements appear insufficient to identify a substantial proportion of individuals at increased risk for future CVD. Indeed, conventional resting BP appears relatively normal in most participants, whereas nearly all demonstrated abnormalities in at least one BP-related outcome early in the rehabilitation period. These results underscore the need for routine 24-hour ambulatory BP monitoring during inpatient rehabilitation, as comprehensive early monitoring is essential for accurate cardiovascular risk stratification, timely intervention, and management of abnormal BP regulation at an early stage. When BP disturbances are identified, clinicians should consider a more detailed cardiovascular risk assessment and evaluate potentially modifiable contributors. Particular attention should be paid to conditions commonly observed after SCI, such as obstructive sleep apnea, as treatment of this condition may reduce nighttime BP (41).

Furthermore, the treatment of BP dysregulation is likely to require a multimodal approach. In addition to pharmacological treatment, lifestyle modifications, such as salt restriction, weight control, and improved sleep hygiene, should be incorporated.

Limitations

This study has several limitations that should be acknowledged. First, the heterogeneous nature of our cohort, consistent with many previous studies in SCI, may limit the generalizability of the findings to the entire SCI population. Nevertheless, the uniform patterns of abnormal BP regulation across participants strengthen the robustness of our conclusions and provide valuable insights into early disturbances in BP regulation following injury. Second, although ambulatory BP monitoring is considered the gold standard for assessing circadian BP patterns, short-term fluctuations related to autonomic dysreflexia or orthostatic hypotension may not have been fully captured. Inability to detect such fluctuations would underestimate the true magnitude of BP variability in this population, further supporting our main conclusions. Finally, potential confounders such as medication use, cardiometabolic risk factors, and physical activity could not be completely controlled for. Although physical activity is a well-established determinant of BP variability, our objective measurements revealed no change in daily standing and stepping time during rehabilitation, suggesting minimal influence on our results (32).

Conclusions

This study demonstrates that disturbances in circadian BP regulation are already evident early after injury in a vast majority of individuals with motor incomplete SCI, characterized by the absence of nocturnal dipping, high SBP variability, and nocturnal hypertension. These abnormalities persisted throughout inpatient rehabilitation, indicating early and sustained autonomic cardiovascular dysregulation that may predispose these individuals to long-term cardiovascular risk. An important observation in this context is that these abnormal nocturnal BP patterns, high BP variability, and nocturnal hypertension were observed in the presence of relative 'normal' daytime BP levels when applying conventional cutoff thresholds used in individuals without SCI. Therefore, routine ambulatory 24-hour BP monitoring during subacute inpatient rehabilitation seems to be essential for early detection and management of BP abnormalities, thereby enabling early risk management and potentially improving cardiovascular outcomes after SCI.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT and Microsoft 365 Copilot in order to assist with spelling, grammar, and improving scientific writing style. After using these tools, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Supplemental data

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