Cerebral autoregulation in people with cervical spinal cord injury during normothermic and cold conditions

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● Abstract

Aim: To study dynamic cerebral autoregulation (CA) in people with cervical spinal cord injury (CSCI) during mild whole-body cold stress leading to a moderate increase in mean arterial pressure (MAP).
Methods: Participants were men with complete autonomic CSCI sustained >4y ago (n=6) and age-matched able-bodied men (n=7). Experiments consisted of 10 minutes of supine normothermic conditions (330C water through a thin-tubed whole-body suit), followed by 20 minutes of mild cold stress (250C). Measurements included respiratory responses, body temperature, cardiovascular responses, spectral analyses and transfer function analyses (coherence, phase and gain averaged over 0.07-0.20 Hz). ANOVA was used to calculate effects of group, condition and group x condition.
Results: One participant with CSCI and one AB participant were excluded from statistical analyses given a decrease in MAP during cold stress. MAP increased on average by +5 (CSCI) or +4 mm Hg (AB) (p=0.008). Coherence appeared to be similar (p=0.500), phase significantly shorter (p=0.011) and gain borderline significantly higher (p=0.077) in the group CSCI compared to the AB group. Group x condition interactions suggested enhanced dynamic CA in the group with CSCI during normothermic conditions, in contrast to the AB group (coherence: p=0.016; phase: p=0.056; gain: p=0.390).
Conclusion: Findings suggest: (1) impaired dynamic CA in people with CSCI; and (2) enhanced dynamic CA in people with CSCI during a moderate increase in MAP caused by whole-body mild cold stress. An explanation for the impaired dynamic CA could be the relatively large dependence on sympathetic control for transient changes in MAP. The enhanced dynamic CA might be related to dynamic CA being more effective during normotensive conditions. Findings imply the need for anti-hypotensive interventions that potentially reduce the risk of cerebrovascular conditions in people with CSCI.

Key words: spinal cord injury, cerebral blood flow, cerebral autoregulation

● Findings

[Background]

Lack of sympathetic control leads to poor blood pressure regulation in people with cervical spinal cord injury (CSCI) [1]. Common consequences are resting hypotension, hypotensive bouts caused by orthostatic intolerance and uncontrolled bouts of extreme hypertension (autonomic dysreflexia) [1]. These extremes in mean arterial pressure (MAP) increase cerebrovascular risk if cerebral hypoperfusion or hyperperfusion is not prevented [2-4]. This requires adequate cerebral autoregulation (CA) [5]. CA refers to mechanisms that act to maintain cerebral blood flow (CBF) during changes in MAP by adjusting cerebrovascular resistance [5]. CA is most effective during normotensive conditions and less effective during periods of hypotension or hypertension [5].

The physiological underpinnings of CA are not yet clear, but important regulators appear to be myogenic factors (e.g. smooth muscle responding to stretch), metabolic factors (e.g. nitric oxide released from endothelium in response to changes in O2) and sympathetic control [5, 6]. Some of these regulators are impaired in people with CSCI, for example due to lack of sympathetic control and endothelial dysfunction [3].

CA is often characterized by a static and a dynamic component [7]. Static CA is described by the steady-state relationship between MAP and CBF; for example comparing the change in CBF averaged over a 2-min period before and during lower-body negative pressure [8]. Dynamic CA is described by transient changes in MAP and CBF; for example studying the effect of spontaneous MAP variability on CBF variability [9]. Dynamic CA is commonly studied using spectral analyses of changes in CBF and MAP to calculate transfer function coherence, phase and gain [9, 10]. Higher coherence and gain as well as a shorter phase are seen as reflecting more impaired dynamic CA (and vice versa) [9].

A recent review indicated that static CA is impaired in people with recently acquired CSCI, but not in people with long-standing CSCI [3]. This suggests adaptation in the months after injury [3]. Myogenic

or metabolic factors might for example adapt to compensate for the lack of sympathetic control and endothelial dysfunction in people with CSCI [3, 8].

It is not clear if such adaptations are sufficient to prevent impaired dynamic CA in people with long-standing CSCI. The dependency on sympathetic control may be larger for dynamic CA compared to static CA [6]. Contradictory results have been found in the few studies available on dynamic CA in people with CSCI [11-13]. Those studies were however limited by the methods used to calculate transfer function. The hypothesis of impaired dynamic CA in people with CSCI should be tested using a method that optimizes reliability of transfer function analyses: the use of weighting based on coherence when averaging phase and gain over a spectral frequency bandwidth [10].

Some of the previous results also suggest that dynamic CA worsens during an orthostatic challenge leading to a decrease in MAP [11, 12]. This indicates that dynamic CA is less effective during exacerbated hypotension. Not known is whether dynamic CA is enhanced during a moderate increase in MAP that leads to a more normotensive state in which CA can be more effective. If so, it provides potential for using interventions to alleviate chronic hypotension and thereby reducing cerebrovascular risk.

For studying a moderate increase in MAP, stimuli such as cold pressure tests of the hand or foot in people with CSCI may not be useful; autonomic dysreflexia could occur [14-16]. An alternative could be mild whole-body cold stress. The mild stress may prevent autonomic dysreflexia, while available sensory feedback could result in vasoconstriction of blood vessels that a participant with CSCI still has control of.

The purpose of this study was to use respiratory responses, body temperature, cardiovascular responses, spectral analyses and transfer function analyses to study dynamic CA of people with CSCI and able-bodied (AB) people during normothermic conditions and during mild-whole body cold stress. We hypothesized that the transfer function analyses would indicate: (1) impaired dynamic CA in the group with CSCI compared to AB people; and (2) enhanced dynamic CA in people with CSCI when comparing normothermic conditions to mild whole-body cold stress leading to a moderate increase in MAP.

[Methods]

Participants

Participants were men with a complete autonomic CSCI and age-matched able-bodied men (Table 1). The criterion to determine autonomic completeness was a plasma noradrenaline level < 94 pg/mL (similar to 0.56 nmol/L) [12]. Exclusion criteria comprised CSCI < 1 year and electrocardiographic abnormalities such as arrhythmia. All participants provided written informed consent after being informed about the study. The study was approved by the Medical Ethical Committee of Wakayama Medical University (Wakayama, Japan).

Procedures

Participants fasted for at least 4 hours before the experiments. During the experiments, ambient temperature in the laboratory was 27.5-28.6 0C, while relatively humidity was 40-45%. Participants were placed on a table in a supine position. For approximately 30-60 minutes, participants were resting while being prepared for the experiments. To prevent pressure sores, participants with CSCI were lifted for one minute - still in a supine position - from the table every 20 minutes. Preparations included putting on a thin-tubed whole-body suit through which water could be conducted. Measurements were then conducted during 10 minutes of normothermic conditions (330C water through the suit), followed by 20 minutes of mild cold stress (250C water through the suit). In between the normothermic and cold condition, participants with CSCI were lifted for one minute.

Measurements

Spirometry was used to measure end-tidal PCO2, end-tidal PO2, oxygen uptake and respiratory rate (ARCO). Core temperature was measured at a sample frequency of 2 Hz using an oesophageal sensor [17]. Skin temperature was measured at 7 sites: forehead, chest, abdomen, upper arm, lower arm, thigh and calf. Electrocardiography (ECG) was conducted using a three-lead system (MU-323R, Nihon Koden Corp., Tokyo, Japan). Impedance cardiography was used to measure stroke volume and cardiac output at a sample frequency of 1 Hz (PhysioFlow Lab-1, Manatec Biomedical, Paris, France). Systolic and diastolic blood pressure were measured each minute using an upper-arm cuff (Tango+, SunTech Medical Inc., Morrisville, NC, USA). Continuous blood pressure was measured at 200 Hz using finger photoplethysmography. CBF velocity was measured at 200 Hz in the middle carotic artery using transcranial Doppler. A 2-MHz probe was placed over the participant's temporal window. It was fixed at a constant angle with a probe holder that was custom-made to fit each participant's facial bone structure. The Doppler sample volume was adjusted to the proximal segment of the MCA. The optimal signal was obtained by trying different angles and positions of

the probe.

Data processing

PetCO2, PetO2, oxygen uptake and respiratory rate were calculated breath-by-breath. Mean skin temperature was calculated based on weighting of each site: forehead (0.07), chest (0.175), abdomen (0.175), upper arm (0.1), lower arm (0.1), thigh (0.2) and calf (0.16) [ref]. MAP measured with the upper-arm cuff was approximated by: diastolic pressure plus one third times pulse pressure.

Data over the last 5 minutes of both conditions was selected for further analyses. A different time window with steady-state body temperature was selected if data contained artifacts. Only 4 or 4.5 min of artifact-free CBF velocity data was available for 3 participants (rest: n=2; cold: n=1). The mean over the selected window was calculated for all outcome measures.

Heart rate was based on peak-to-peak intervals of the continuous blood pressure signal, as technical problems with the ECG occurred in 6 participants. Beat-to-beat MAP and CBF velocity were obtained by integrating the respective signals within each cardiac cycle. Cardiac cycles were based on the valley-to-valley intervals of the continuous blood pressure signal, which coincided with the valley-to-valley intervals of the CBF velocity signal.

Beat-to-beat MAP and CBF velocity were first linearly interpolated and resampled at 2 Hz and then detrended by subtracting their 3rd order polynomial [9, 18]. Following, the beat-to-beat time series were used for spectral and transfer function analyses based on the Welch algorithm [9]. Each time series was subdivided into successive 256-point Hann windows that overlapped by 50% before fast Fourier transform analysis [9, 10]. This resulted in a spectral resolution of 0.0020 Hz in all but two participants (0.0039 Hz).

The cross-spectrum between MAP and CBF velocity was determined and divided by the MAP autospectrum to derive the transfer function coherence, gain and phase [9]. Coherence reflects the linear correlation between changes in MAP and changes in CBF velocity (index of 0-1). Gain reflects the magnitude with which changes in CBF velocity are driven by MAP (cm/s per mm Hg). Phase reflects the time delay between changes in MAP to be reflected in changes in CBF velocity (radians).

Spectral power of MAP and CBF velocity as well as coherence, gain and phase were averaged over the low-frequency bandwidth of 0.07-0.20 Hz [9]. The low-frequency bandwidth appears to be the most established bandwidth and is considered to reflect sympathetic influences on the vasculature [3, 12, 19]. The contribution of gain and phase toward the band average was weighted according to their individual precision, which depended on coherence at each spectral frequency [10].

Statistical analyses

Previous research showed a minimal sample size of N=4 to find significant differences in dynamic CA in people with CSCI [20]. Parametric statistics were applied to all outcome measures with a normal distribution, which was assessed using Shapiro-Wilks tests ($p<0.05$). Data was log-transformed if the Shapiro-Wilk test indicated a non-normal distribution. A 2x2 ANOVA was used to analyze the main effects of group and condition as well the interaction effect of group x condition. The significance level was set at $p<0.05$.

[Results]

Five participants with CSCI and 6 AB participants were included in the statistical analyses (Tables 1 and 2). One participant with CSCI and one AB participant (Table 1) were excluded from the analyses as they did not show the anticipated response during the cold condition: MAP decreased from normothermic to the cold condition (respectively -7 or -10 mm Hg).

Respiratory responses

Intraindividual differences in end-tidal PetCO2 showed differences ranging from -2.5 to 1.6 mm Hg (CSCI) and -0.4 to 1.8 mm Hg (AB). Delta scores indicate negligible intraindividual differences for end-tidal PO2, oxygen uptake and respiratory rate over the two conditions (Table 2). Respiratory rate of most participants during both conditions was >0.20 Hz, indicating that respiratory rate did not influence spectral analyses over the low-frequency bandwidth of 0.07-0.20 Hz (Table 2). Exceptions were one participant with CSCI (normothermic and cold: 0.16 Hz) and one AB participant (normothermic: 0.13 Hz; cold: 0.14 Hz).

Body temperature

Body temperature appeared to respond similarly to the cold condition when comparing the group with CSCI with the AB group (Table 2). There was no significant decrease in oesophageal temperature, while mean skin temperature decreased significantly by on average -2.3 0C (CSCI) and -1.4 0C (AB).

Cardiovascular responses

Heart rate and finger MAP were significantly lower in the group with CSCI compared to the AB group (Table 2). Cardiovascular responses appeared to be

similar between the groups. A significant reduction in heart rate (on average -2 beats/min) seemed to induce a significant decrease in cardiac output (on average -0.2 or -0.4 L/min for CSCI and AB respectively), as stroke volume did not change significantly (Table 2). All blood pressure outcomes showed a significant increase (Table 2). MAP measured with the upper arm cuff increased on average by +5 (CSCI) or +4 mm Hg (AB) (Figure 1). CBF velocity was not significantly different between groups or conditions.

Spectral analyses

Spectral power of MAP – averaged over the low-frequency bandwidth of 0.07-0.20 Hz – was significantly lower in the group with CSCI compared to the AB group (Table 2). Spectral power of CBF velocity showed large interindividual differences within both groups, but was not significantly different between the groups. No significant differences were found between conditions.

Transfer function analyses

A significant group difference was found for phase (Figure 2 and Table 2). It was significantly shorter in the group with CSCI (-0.1 vs. 0.6 radians on average during the normothermic condition). The negative phase in the group with CSCI indicates that changes in CBF velocity were leading changes in MAP. No significant group difference was found for coherence or gain (Figure 2 and Table 2). However, gain was borderline significantly higher (p=0.077) in the group with CSCI compared to the AB group (1.7 vs. 0.8 cm/s per mm Hg on average during the normothermic condition).

A significant interaction term was found for coherence (p=0.016), while it was borderline significant for phase (p=0.056). When comparing cold to normothermic conditions, coherence appeared reduced in the group with CSCI and increased in the AB group (Figure 2). Similarly, phase seemed lengthened in the group with CSCI and shortened in the AB group.

[Discussion]

First, the transfer function analyses suggest that dynamic CA was impaired in the group with CSCI compared to the AB group. Transfer function phase was significantly shorter, while gain was borderline significantly higher in the group with CSCI. Second, dynamic CA appeared to be enhanced in the group with CSCI when comparing the cold to the normothermic condition. Coherence seemed reduced in the group with CSCI and increased in the AB group, while phase seemed lengthened in the group with CSCI and shortened in the AB group.

Similar to our findings, impaired dynamic CA indicated by a longer phase and higher gain was also found in two previous studies [11, 12], in contrast to another [13]. This discrepancy might be explained by methodological differences in using transfer function analyses for assessing dynamic CA [10]. Reliability of phase and gain depends on the assumption that a linear relationship exists between the autospectra of MAP and CBF velocity [9, 10]. Low coherence indicates that a linear relationship does not exist or that signal-to-noise ratio is insufficient [9]. Dealing with low coherence is therefore a prerequisite when using phase and gain [10]. This was not done in the one study that found no impairments in dynamic CA of people with CSCI [13]. The others used an arbitrary coherence cut-off of 0.5 [11, 20], but this can also bias results [10]. Our results are the first in CSCI based on the preferred method for dealing with low coherence: the use of weighting based on coherence when averaging phase and gain over a spectral frequency bandwidth [10]. Our findings substantiate the hypothesis that dynamic CA is impaired in people with CSCI [3, 11, 12].

Lack of sympathetic control and endothelial dysfunction are possible causes for impaired dynamic CA in people with CSCI [3]. Although still debated [5, 21], evidence is emerging for sympathetic control as one of the regulating factors of CA [6, 18, 22, 23]. A shorter phase and larger gain were for example found in AB groups after sympathetic blockade [6, 18]. Static CA seems unaffected by sympathetic blockade [6]. This suggests that the relative contribution of sympathetic control to CA is larger when faced with transient changes in MAP compared to slower changes in MAP [6, 18].

A relatively small contribution of sympathetic control to static CA might explain why static CA seems unaffected in people with CSCI [3]. Our data also indicate this; CBF velocity remained constant while MAP showed a similar moderate increase in both groups. People with recently acquired CSCI do show impaired static CA [3], indicating that adaptations occur in the months after injury. A likely adaptation is that other regulating factors of CA – for example of myogenic or metabolic nature – might compensate for the lack of sympathetic control [3, 8]. Perhaps such adaptations are sufficient for maintaining static CA, but not for dynamic CA when assuming the latter depends more on sympathetic control. Another suggested adaptation is sympathetic fibers shortcutting the cervical ganglia [8]. This seems unlikely based on our data, as shortcutted sympathetic control could be expected to prevent impaired dynamic CA.

The (borderline) significant interactions for coherence and phase suggest enhanced dynamic CA in the group with CSCI when experiencing an increase in MAP caused by the cold stress, in contrast to the AB group who showed on average higher coherence and a shortened phase. It is possible that the group with CSCI experienced a temporary alleviation of hypotension, leading to more normotensive conditions that allowed more effective dynamic CA. The AB group might have experienced relative hypertension. We speculate that effectiveness of dynamic CA in people with CSCI – even when it is impaired due to lack of sympathetic control – still depends on MAP levels, similar to AB people [5]. This is substantiated by previous results suggesting that dynamic CA is more impaired in people with CSCI during exacerbated hypotension [11, 20].

Impaired dynamic CA might be one of the underlying factors for the increased risk of cerebrovascular conditions such as stroke and cognitive decline in people with CSCI [2-4]. For example, impaired dynamic CA might contribute to the negative effects of resting hypotension on cerebral hypotension related to cognitive decline. [4, 25]. Impaired dynamic CA during a surge in MAP, such as during autonomic dysreflexia, could predispose to hemorrhagic stroke [26]. Autonomic dysreflexia includes uncontrolled activation of the sympathetic nervous system. If and how this relates to dynamic CA could be further elucidated by studying dynamic CA during spontaneous episodes of autonomic dysreflexia.

Our data suggests that alleviating resting hypotension enhances dynamic CA in people with CSCI. This implies potential for using anti-hypotensive interventions to reduce cerebrovascular risk in people with CSCI. Promising anti-hypotensive interventions such as with midodrine require follow-up, as it is not yet clear whether these drugs can improve dynamic CA in people with CSCI [11].

Some evidence is emerging on the relative contribution of different regulatory factors for CA in AB people [23]. More research on these relative contributions – in AB people and in people with CSCI – can help understand the adaptations in regulatory factors of CA that seem to occur after sustaining CSCI [3, 8]. This could help determine if and what interventions could support positive adaptations in people with recently acquired CSCI as well as long-standing CSCI.

[Limitations]
A first limitation is the small sample size limiting statistical power. Still, we found significant differences, similar to other studies based on samples as small as N=4 [12]. Second, CBF velocity quantified by transcranial Doppler ultrasound represented CBF only if the diameter of the middle cerebral artery remained constant [5]. This assumption can be violated during conditions of hypoxia, very high arterial pressures of oxygen, hypoxia or dramatic changes in blood pressure [5]. These did not seem to occur in our study. Third, end-tidal PCO2 was not constant in all participants over the normothermic and cold conditions. CBF is very sensitive to changes in arterial PCO2 and can be reflected by end-tidal PCO2 [24]. Potential confounding influence on our findings cannot be excluded, but may have been limited. Differences in end-tidal PCO2 were relatively small (-2.5 to 1.8 mm Hg) and both positive and negative, presumably cancelling out differences on a group level. Last, interpretation of dynamic CA was based on linear relationships inherent to transfer function analyses [9]. This overlooks potential non-linear relationships in CA [7]. We speculate that this limitation does not influence our conclusions, since a potential confounding effect might have affected both groups and conditions similarly.

[Conclusions]
Our data suggest impaired dynamic CA in people with CSCI. A possible explanation is that still functioning regulating factors of CA are not able to compensate for the lack of sympathetic control, which appears to be relatively important during transient changes in MAP [6]. Our data also suggest that dynamic CA in people with CSCI is enhanced during a moderate increase in MAP caused by whole-body mild cold stress. A possible explanation is that the more normotensive condition during cold provided a MAP range in which CA was more effective. These conclusions are limited by the sample size and interpretation of dynamic CA using linear relationships only. Findings reinforce the need for anti-hypotensive interventions for people with CSCI, as this could reduce the relatively high risk of cerebrovascular conditions of people with CSCI [2-4].

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Table 1. Participant characteristics

Participant	Age (y)	Height (m)	Body weight (kg)	Noradrenalin (pg/ml)	Adrenalin (pg/ml)	Time since injury (y)	Lesion level
CSCI 1	33	1.90	73.0	69	15	16	C6
CSCI 2	24	1.80	64.3	29	5	9	C6
CSCI 3	42	1.66	41.8	77	5	25	C5/6
CSCI 4	33	1.75	55.0	20	5	5	C6
CSCI 5	48	1.81	80.8	86	5	30	C5
CSCI 6*	25	1.72	46.1	32	11	4	C6
Median CSCI	33	1.78	59.7	51	5	13	
AB 1	67	1.77	61.9	138	32		
AB 2	39	1.68	61.0	339	33		
AB 3	44	1.80	75.3	176	26		
AB 4	32	1.73	69.0	219	39		
AB 5	28	1.75	64.2	188	98		
AB 6	29	1.65	60.1	184	35		
AB 7*	30	1.78	71.8	312	58		
Median AB	32	1.75	64.2	188	35		

*Excluded from statistical analyses as MAP decreased during the cold condition.
Abbreviations: CSCI = cervical spinal cord injury; AB = able-bodied

Figure 1. Mean and standard deviation of mean arterial pressure (MAP) and transfer function coherence, phase and gain in the group with cervical spinal cord injury (CSCI) and the able-bodied (AB) group, including the 2x2 ANOVA (G=group; C=condition; GxC = interaction).

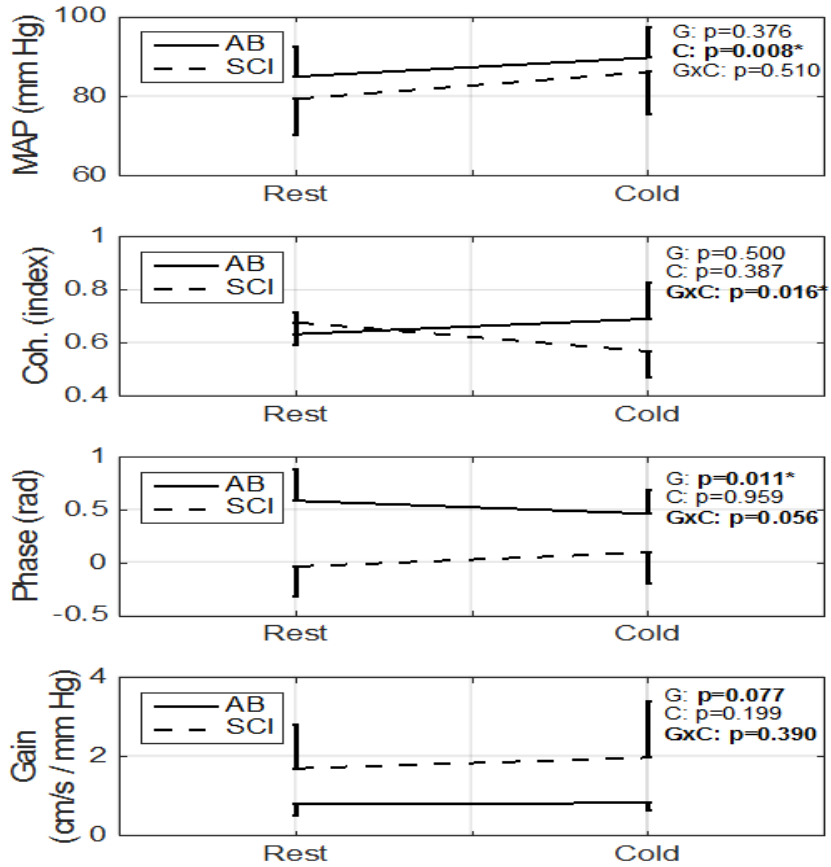

Table 2. Outcome measures and comparisons within and between the groups during the normothermic and cold conditions. Values in median (interquartile range).

	Group with CSCI (*n*=5)			AB group (*n*=6)			2x2 ANOVA		
	Normothermic	**Cold**	**Delta**	**Normothermic**	**Cold**	**Delta**	**Group**	**Condition**	**Interaction**
Respiratory responses									
End-tidal P_{CO2} (mm Hg)	37.9 (35.8-39.1)	37.6 (35.8-38.4)	0.6 (-2.3-1.1)	39.9 (36.7-42.2)	40.4 (37.5-42.3)	0.2 (-0.4-1.5)	N/A	N/A	N/A
End-tidal P_{O2} (mm Hg)	107 (106-113)	110 (106-112)	0 (-4-4)	107 (104-108)	106 (104-107)	0 (-2-1)	N/A	N/A	N/A
Oxygen uptake (ml/min)	236 (158-239)	182 (128-225)	-21 (-64-3)	210 (129-261)	210 (176-276)	9.9 (-4.5-61.7)	N/A	N/A	N/A
Respiratory rate (Hz)	0.26 (0.19-0.35)	0.27 (0.18-0.36)	0.01 (-0.03-0.02)	0.26 (0.20-0.30)	0.28 (0.22-0.30)	0.01 (-0.02-0.04)	N/A	N/A	N/A
Body temperature									
Oesophageal temperature (^{0}C)	36.8 (36.2-37.1)	36.6 (36.2-37.1)	-0.1 (-0.2-0.0)	36.8 (36.6-36.8)	36.7 (36.7-36.8)	0.0 (-0.1-0.1)	0.858	0.152	0.152
Mean skin temperature (^{0}C)	34.4 (34.2-35.1)	32.2 (32.0-33.1)	-2.3 (-2.4--1.7)	35.0 (34.5-35.4)	33.2 (32.7-33.8)	-1.6 (-2.1--1.3)	0.158	0.000	0.120
Cardiovascular responses									
Heart rate (b/min)	55 (51-61)	55 (50-59)	-2 (-2-0)	69 (64-76)	67 (61-73)	-2 (-6-0)	**0.024***	**0.020***	0.387
Stroke volume (mL)	81 (60-92)	86 (60-91)	0 (-2-3)	76 (73-82)	79 (70-82)	0 (-3-3)	0.984	0.663	0.745
Cardiac output (L/min)	5.0 (3.3-5.7)	4.8 (3.2-5.5)	-0.2 (-0.3-0.0)	5.6 (4.4-6.4)	5.4 (4.3-5.9)	-0.4 (-0.6-0.0)	0.222	**0.014***	0.265
SBP upper-arm cuff (mm Hg)	104 (92-120)	109 (105-125)	9 (1-14)	113 (107-125)	117 (116-126)	5 (2-9)	0.263	**0.003***	0.445
DBP upper-arm cuff (mm Hg)	66 (61-72)	69 (63-84)	2 (-1-16)	72 (66-74)	77 (69-80)	4 (3-6)	0.573	**0.022***	0.673
MAP upper-arm cuff (mm Hg)	75 (73-88)	82 (78-96)	5 (1-14)	85 (80-91)	91 (85-94)	4 (3-7)	0.376	**0.006***	0.547
MAP finger (mm Hg)	63 (54-68)	74 (59-84)	7 (5-18)	78 (74-85)	84 (77-96)	11 (-4-15)	**0.013***	**0.018***	0.529
CBF velocity (cm/s)	70 (49-83)	81 (45-86)	2 (-5-7)	65 (53-75)	67 (49-76)	0 (-5-4)	0.719	0.598	0.900
Spectral analyses									
Power MAP finger (mm Hg^2/Hz)	2.2 (1.4-3.3)	2.2 (1.6-3.2)	0.0 (-1.0-1.1)	14.3 (6.5-33.3)	22.6 (5.8-47.7)	5.2 (-0.1-14.4)	0.049*	0.133	0.138
Power CBF velocity ([cm/sec]^2/Hz)	3.5 (1.5-21.7)	6.7 (4.2-20.2)	0.2 (-1.5-4.2)	6.5 (5.2-23.3)	10.0 (4.3-26.7)	-0.4 (-2.7-6.9)	0.592$^{\#}$	0.538$^{\#}$	0.891$^{\#}$
Transfer function analyses									
Coherence (index of 0-1)	0.69 (0.60-0.76)	0.58 (0.49-0.65)	-0.14 (-0.19--0.02)	0.63 (0.57-0.68)	0.73 (0.59-0.78)	0.07 (-0.02-0.14)	0.500	0.387	**0.016***
Phase (radians)	-0.1 (-0.3-0.3)	0.0 (-0.1-0.4)	0.2 (-0.1-0.3)	0.6 (0.3-0.8)	0.5 (0.3-0.7)	-0.1 (-0.3-0.0)	**0.011***	0.510	**0.056**
Gain (cm/s per mm Hg)	1.7 (0.8-2.6)	1.6 (1.1-3.1)	0.1 (0.0-0.7)	0.8 (0.6-1.0)	0.8 (0.7-1.0)	0.0 (-0.1-0.2)	**0.077**	0.199	0.390

Abbreviations: CSCI = cervical spinal cord injury; AB = able-bodied; SBP = systolic blood pressure; DBP = diastolic blood pressure; MAP = mean arterial pressure; CBF = cerebral blood flow

*$p<0.05$

$^{\#}$ANOVA applied after log transformation.

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