Cerebral critical closing pressure and CO₂ responses during the progression toward syncope

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Cerebral critical closing pressure and CO₂ responses during the progression toward syncope. J Appl Physiol 114: 801–807, 2013. First published January 31, 2013; doi:10.1152/japplphysiol.01181.2012.—Syncope from sustained orthostasis results from cerebral hypoperfusion associated with reductions in arterial pressure at the level of the brain (BP_{MCA}) and reductions in arterial CO₂ as reflected by end-tidal values (PETCO₂). It was hypothesized that reductions in PETCO₂ increase cerebrovascular tone before a drop in BP_{MCA} that ultimately leads to syncope. Twelve men (21–42 yr of age) completed an orthostatic tolerance test consisting of head-up tilt and progressive lower body negative pressure to presyncope, before and after completing 5 days of continuous head-down bed rest (HDBR). Cerebral blood velocity (CBFV), BP_{MCA}, and PETCO₂ were continuously recorded throughout the test. Cerebrovascular indicators, cerebrovascular resistance, critical closing pressure (CrCP), and resistance area product (RAP), were calculated. Comparing from supine baseline to 6–10 min after the start of tilt, there were reductions in CBFV, PETCO₂, BP_{MCA}, and CrCP, an increase in RAP, and no change in cerebrovascular resistance index. Over the final 15 min before syncope in the pre-HDBR tests, CBFV and CrCP were significantly related to changes in PETCO₂ (r = 0.69 ± 0.17 and r = 0.63 ± 0.20, respectively), and BP_{MCA}, which was not reduced until the last minute of the test, was correlated with a reduction in RAP (r = 0.91 ± 0.09). Post-HDBR, tilt tolerance was markedly reduced, and changes in CBFV were dominated by a greater reduction in BP_{MCA} with no relationships to PETCO₂. Therefore, pre-HDBR, changes in PETCO₂, with orthostasis contributed to increases in cerebrovascular tone and reductions in CBFV during the progression toward syncope, whereas, after 5 days of HDBR, orthostatic responses were dominated by changes in BP_{MCA}.

Zuj KA, Arbeille P, Shoemaker JK, Hughson RL. Cerebral critical closing pressure and CO₂ responses during the progression toward syncope. J Appl Physiol 114: 801–807, 2013. First published January 31, 2013; doi:10.1152/japplphysiol.01181.2012. —Syncope occurring with prolonged orthostasis results from a reduction in cerebral perfusion and is normally associated with a large, rapid reduction in arterial blood pressure at the level of the middle cerebral artery (BP_{MCA}) (5, 8, 18, 19). A reduction in cerebral blood flow velocity (CBFV) with the progression toward syncope has been attributed by some researchers to a reduction in the partial pressure of arterial carbon dioxide (PaCO₂) (5, 6, 18, 21). However, other work has suggested a poor relationship between PaCO₂ and changes in CBFV, at least during the early phase of orthostasis (13, 34). Thus the mechanisms underlying reduced CBFV in the approach to syncope have not been clearly identified.

Assessment of cerebrovascular hemodynamics frequently relies on measurement of CBFV and calculation of cerebral vascular resistance or conductance, but these measures may not fully explain alterations in cerebrovascular properties. The calculations of critical closing pressure (CrCP) and resistance area product (RAP) have been used to further describe cerebral hemodynamic changes with exercise (23), alterations in end-tidal PCO₂ (PETCO₂) (1, 25, 26), and neurovascular coupling with cognitive and motor tasks (27). Carey et al. (5) showed changes in both CrCP and RAP with approaching syncope, but did not relate these changes directly to alterations in PETCO₂ or BP_{MCA}. Further analysis of CrCP and RAP may help to better describe cerebrovascular hemodynamic responses to orthostasis, since CrCP reflects changes in cerebrovascular tone, while RAP, as an index of cerebrovascular resistance (CVRi), does not make the assumption that cerebral perfusion pressure gradient is referenced to 0 mmHg (9, 25). Recently, Paneri et al. (27) advanced the hypotheses that RAP is related to myogenic properties of the cerebrovascular system, while CrCP reflects metabolism and cerebrovascular reactivity to CO₂.

Cardiovascular deconditioning from exposure to real or simulated microgravity impairs orthostatic tolerance (2, 4, 40). The potential contributions of change in PETCO₂ and the cerebrovascular response to CO₂ have not been investigated with respect to this reduction in tolerance. Animal models provided a basis to suspect change, as the nitric oxide system that has been linked to cerebrovascular CO₂ reactivity (16, 17, 32) is downregulated with simulated microgravity (20, 29, 38). Recent observations of reduced cerebrovascular CO₂ reactivity in astronauts returning from long-duration spaceflight (41) further suggest that these factors should be investigated following head-down bed rest (HDBR). To date, no studies have been conducted examining the relationship between blood pressure, PETCO₂, cerebral blood flow, and cerebrovascular tone with the progression toward syncope before and after exposure to simulated microgravity.

The following study provided the opportunity to examine cerebrovascular responses to head-up tilt sustained to presyncope, both before and after exposure to simulated microgravity, with particular emphasis on the influences of changes in arterial pressure and PETCO₂. It was hypothesized that, with the progression toward syncope, there would be a reduction in CBFV related primarily to the change in PETCO₂ and not BP_{MCA} and that the reduction in CBFV would be associated with an increase in CrCP, indicating increased cerebrovascular tone. Post-HDBR, it was hypothesized that these relationships with the progression toward syncope would remain consistent, but changes would occur sooner after tilt due to a reduction in orthostatic tolerance. Additionally, it was hypothesized that the initial tilt responses would show greater changes post-HDBR, also related to a reduction in orthostatic tolerance.

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METHODS

Experimental protocol. Twelve healthy men (21–42 yr of age) were tested before and after 5 days of strict, continuous 6° HDBR. All experimental procedures were approved by the Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale, Midi-Pyrénées (France) and local ethics committees, including the Office of Research Ethics, University of Waterloo. The entire protocol was in accordance with the declaration of Helsinki. Each subject signed a consent form after receiving full disclosure of the experimental protocol and was aware of his right to withdraw from the study for any reason without prejudice.

All subjects completed a medical screening before entry into the study to ensure normal health with no contraindications, including, but not limited to, orthostatic intolerance, chronic back pain, and elevated blood pressure. The baseline characteristics of the subjects included body mass (75 ± 8 kg), height (178 ± 8 cm), and maximal oxygen uptake (39.3 ± 6.5 ml kg−1 min−1). Subjects were considered to be recreationally active; none was in athletic training.

Orthostatic tolerance, tilt testing was conducted 2 days before the start of HDBR (pre-HDBR) and as the first transition to an upright posture after the 5 days of HDBR (post-HDBR). Following instrumentation (~15 min in the supine position), baseline data were collected for 5 min in the supine position. Participants were then passively tilted to an 80° head-up position, where they were required to stand quietly for 30 min. If signs of orthostatic intolerance did not occur within this time (for 10 of 12 subjects in pre-HDBR), lower body negative pressure (LBNP) was progressively applied with step decreases of −10 mmHg every 3 min. Testing continued until one or more of the following test termination criteria were met: systolic blood pressure <70 mmHg, a sudden drop in heart rate (>15 beats/min), severe light headedness, nausea, or the request of the subject to terminate the test. No differences in responses were evident in pre-HDBR testing between subjects with presyncpe before LBNP vs. with LBNP, so all results were pooled.

A standard three-lead electrocardiogram (Roxon Medi-Tech, St. Leonard, QC, Canada) was recorded. Finger photoplethysmography (Nexfin, BMEYE BV, Amsterdam, the Netherlands) was used for the continuous assessment of arterial blood pressure. Values recorded in the finger were corrected to heart level. Postprocessing of the blood pressure signal involved the correction of recorded values to a manual blood pressure measure, taken by a trained experimenter before the start of the tilt test with the subjects resting in a supine position. An additional height correction was also applied during postprocessing to determine BP_MCA. Participants were equipped with a nasal cannula for monitoring of expired CO2 (Ohmeda 5200 CO2 Monitor, Madison, WI). Values were recorded as percent CO2 to be later converted to millimeters of mercury based on ambient temperature and barometric pressure. Electrocardiogram, BP_MCA, and CO2 data were collected at 1,000 Hz using Chart software (ADInstruments, Colorado Springs, CO).

Blood flow velocity in the MCA (CBFV) was determined using transcranial Doppler ultrasound. A 2-MHz pulsed Doppler probe was placed over the right temporal window, which allowed for the insonation of the M1 segment of the right MCA and the assumption of 0° for the angle of insonation. A head band was used to hold the probe in place throughout the testing. Doppler signals were collected using CardioLab hardware (CNES device, European Space Agency) and were recorded at 100 Hz using CardioMed software (CNES-European Space Agency).

Cerebrovascular variables. Mean CBFV values were calculated from the outer envelope of the Doppler spectrum over a cardiac cycle. The Doppler recording was also assessed to determine maximum (systolic) and minimum (end diastolic) values for each cardiac cycle. An index of CVRi was calculated as CVRi = mean BP_MCA/CBFVmean where CBFVmean is mean CBFV.

Further analysis was conducted with the CBFV waveform for the calculation of CrCP and RAP. Following the methods described in a recent critical analysis (24), CrCP was calculated for each beat using mean (CBFVmean and MAP_MCA) and diastolic (CBFVdia and DBP_MCA) values for CBFV and BP_MCA. The slope of the relationship between CBFV and BP_MCA was calculated as \( a = \frac{(\text{CBFVmean} - \text{CBFVdia})}{(\text{MAP_MCA} - \text{DBP_MCA})} \). RAP was then calculated as \( \text{RAP} = 1/a \), and CrCP calculated as \( \text{CrCP} = \text{MAP_MCA} - (\text{CBFVmean}a) \).

Previous studies of head-up tilt and sustained orthostasis have used a linear regression method for assessing CrCP and RAP (5, 37). However, in this study, the two-point method using mean and diastolic values of CBFV and BPMC MCA was chosen, as it has recently been shown to have greater repeatability and fewer instances of negative CrCP values being calculated (24).

Data analysis. This study reports on data collected during the control; however, the original design of the study included two countermeasure conditions for the same subjects with pre-HDBR data collected three times for each subject. Post-HDBR data for the countermeasure conditions were not included in the present analysis, as only a small number of individuals completed both of the protocols. Previous work has demonstrated good reproducibility of responses to combined tilt and LBNP (18), and statistical analysis of these data (not shown) showed no differences between the pre-HDBR responses defined as the difference between a 5-min average taken at supine baseline, a 5-min average taken between minutes 6–10 of the tilt, and the last minute of the test. Therefore, for analysis purposes, pre-HDBR was considered as the average of all three pre-HDBR data collections.

Variables were assessed beat by beat and then averaged every 10 s pre-HDBR and 5 s post-HDBR after the transition to the tilted position. PETCO2 values were linearly interpolated to determine values for each heartbeat. Early tilt responses were assessed as the difference between a 5-min average taken during supine rest and a 5-min average taken between minutes 6 and 10 of the tilt. For seven tests, following HDBR, the participants were unable to complete 10 min of the stand test. Therefore, tilt values were taken as the average from 5 min post-tilt, excluding the last minute of the test, which included rapid changes in measured variables.

Statistical analysis. The analysis of cardiovascular responses to tilt was performed in several ways to analyze both the transition to tilt and the period of tilt before presyncope. The early phase of tilt was analyzed by comparisons to supine baseline with two-way repeated-measures ANOVA (SAS/Stat 9.2, SAS Institute, Cary, NC). Next, responses were assessed over the final 15 min of the test pre-HDBR and due to the shorter duration of testing post-HDBR, over the final 5 min of the test post-HDBR with one-way repeated-measures ANOVA being used to assess each minute value. Finally, linear regression analysis was used on data from each individual to explore possible interrelationships between different variables. From the data in the final 15 min of the test pre-HDBR, two distinct sections were identified based on the point at which BP_MCA became different from the value at 15 min. BP_MCA was not different until 1 min before syncope; therefore, regressions were performed on data between minutes 15 and 2, and minutes 2 and 0 separately to determine relationships between PETCO2, BP_MCA, CBFV, CrCP, and RAP. Post-HDBR, regressions were performed between minutes 5 and 2 and minutes 2 and 0. Data for the linear regressions are presented as the Pearson product moment correlation (r).

All values are shown as means ± SD, unless otherwise stated. Significance was set at \( P < 0.05 \) for the repeated-measures analysis of variance and \( P < 0.01 \) for linear regression analysis.

Analysis limitations. Data were available for all 12 individuals pre-HDBR; however, post-HDBR, some data were not available for the planned analyses. For the comparison of early tilt responses (average between 5 and 10 min posttilt), three individuals post-HDBR experienced syncope within 5 min of tilt; therefore, only 9 of 12 individuals were included in the repeated-measures analysis. Post-HDBR, the linear regression analysis was attempted for eight of the nine individuals who were able to complete greater than 5 min of tilt, with one individual being excluded as the test was terminated early due to a power outage.
RESULTS

Pre-HDBR, the average tilt tolerance time was 36 ± 10 min, with all but two individuals reaching the LBNP portion of the tolerance test. In comparison, tilt tolerance time was reduced post-HDBR (16 ± 15 min) with 7 of 12 individuals unable to complete 10 min of the test, and 3 of these individuals developing presyncopal symptoms within 3 min of tilt. Plasma volume, assessed by change in hemoglobin, was reduced 16 ± 6% after HDBR.

Analysis of the cerebrovascular early tilt responses, presented in Fig. 1, showed significant reductions in CBFV (A, P < 0.001), PETCO2 (B, P < 0.001), BP_MCA (D, P < 0.001), and CrCP (E, P < 0.001), along with an increase in RAP (F, P = 0.035) and no significant changes for CVRi (C, P = 0.366) both pre- and post-HDBR. A significant interaction was found suggesting a greater reduction in BP_MCA post-HDBR (P = 0.016). There was a weak trend toward a greater reduction in CBFV (P = 0.183), but no differences in early tilt responses with HDBR for any other variable assessed.

The changes in CBFV, PETCO2, and BP_MCA during the last 15 min before syncpe pre-HDBR are presented in Fig. 2. CBFV and PETCO2 progressively decreased with significant reduction from the value at 15 min by 4 min (~10.8 ± 7.0%) and 5 min (~10.1 ± 7.2%) before syncpe, respectively. Conversely, BP_MCA was only different 1 min before and at syncpe, where BP_MCA was reduced by ~8.0 ± 6.0 and ~35.1 ± 11.8%, respectively. Similar to PETCO2, CrCP was significantly increased from the value at 15 min by 5 min before syncpe (4.8 ± 4.2 mmHg), whereas RAP was only reduced at syncpe (~0.5 ± 0.3 mmHg cm⁻¹s⁻¹). Post-HDBR, compared with the value 5 min before syncpe, BP_MCA, PETCO2, and CBFV were all significantly reduced at syncpe (P < 0.05), and there was a trend (P = 0.054) for RAP to also be reduced at syncpe. No changes in CrCP were seen for the post-HDBR data.

Linear regression analysis results pre-HDBR and post-HDBR are presented in Tables 1 and 2, respectively. Pre-HDBR between 15 and 2 min before syncpe, significant relationships were found between CBFV and BP_MCA for only 4 of 12 people, while the relationship between CBFV and PETCO2 was significant in 10 of 12 people (Table 1). This is in contrast to the last 2 min of the test, where only 3 of 12 people had significant relationships between CBFV and PETCO2, whereas 9 of 12 had CBFV significantly related to the change in BP_MCA (Table 1). Post-HDBR, only one individual showed a significant relationship between CBFV and PETCO2 between 5 and 2 min and over the last 2 min of the test (Table 2). However, similar to pre-HDBR, over the last 2 min of the test, significant relationships were found between CBFV and BP_MCA for six of the eight people (Table 2).

A visual display of the interrelationships between PETCO2, BP_MCA, CrCP, and RAP is shown in Fig. 3 for pre-HDBR tests (note the inverted scale for CrCP). Linear regressions were performed on data pairs for these variables between 15 and 2 min before syncpe for each individual. The majority of subjects (Table 1) had significant RAP-BP_MCA and CrCP-PETCO2 relationships in this time interval. In contrast, there were only weak RAP-PETCO2 and CrCP-BP_MCA relationships (Table 1). During the last 2 min of the test, only RAP-BP_MCA was significant in 8 of 12 people (Table 1). In contrast to the
results, there was no significant change in CrCP with approaching syncope (data not shown); however, four of eight people did show significant relationships between CrCP and BP_{MCA} during the last 2 min of the test (Table 2). Similar to pre-HDBR, RAP was significantly related to BP_{MCA} for all individuals between minutes 5 and 2, and for six of eight people during the last 2 min of the test (Table 2).

**DISCUSSION**

This study provided an in depth look at cerebrovascular responses during the final 15 min of an orthostatic challenge, resulting in presyncopal symptoms. In support of the first hypothesis, it was observed that, while BP_{MCA} was unchanged until the final minute before syncope, CBFV and PET_{CO2} were significantly reduced earlier, with 10 of 12 individuals having significant linear relationships between these variables. These findings are consistent with results suggested by some previous research (5, 6, 15, 18), but challenge the suggestion based on prior studies (37), which has the potential for producing negative values for CrCP (24), are more likely reasons for these findings. In contrast to the hypothesis, it was observed that, while BP_{MCA} was unchanged until the final minute before syncope, CBFV and PET_{CO2} were significantly reduced earlier, with 10 of 12 individuals having significant linear relationships between these variables. These findings are consistent with results suggested by some previous research (5, 6, 15, 18), but challenge the suggestion based on prior studies (37), which has the potential for producing negative values for CrCP (24), are more likely reasons for these findings.

Early tilt cerebrovascular responses pre-HDBR. The early responses to tilt were assessed by comparing supine resting values of cerebrovascular variables to an average taken between minutes 5 and 10 after tilt. Responses were consistent with other research observing reductions in BP_{MCA}, CBFV, and PET_{CO2}, after the transition to an upright posture (6, 13, 22, 34), showing the complex interactions of these variables. The absence of significant change in CrCP was somewhat unexpected, as CrCP was reduced by ~20 mmHg, and autoregulatory processes were expected to reduce cerebrovascular resistance to maintain CBFV. However, examination of CrCP and RAP revealed that CBFV was partially preserved by a reduction in CrCP, despite the decrease in PET_{CO2}, which is normally expected to increased CrCP (5), but this benefit was partially offset by an unexpected increase in RAP, with the net result of reduced CBFV during head-up tilt. Thus the early responses to tilt contrasted with the proposal of Pannier et al. (27) that linked RAP to a myogenic response and CrCP to CO2. We found that reduced CrCP appeared to be the major mechanism supporting autoregulation in response to the large myogenic stimulus as CrCP was reduced, supporting other recent observations (37). Regional differences in cerebral blood flow responses to orthostatic stress and PCO2 (30, 31) may have contributed to results observed in the present study, but the impact on CrCP and RAP was not measured in those studies.

The observed increase in RAP and large reduction in CrCP in the present study during 80° head-up tilt contrast with a recent report of no change in RAP and smaller changes in CrCP during an incremental tilt study up to 75° (37). While differences in protocol might have influenced results, the differences in calculation method for CrCP and RAP, with the two-point method involving the mean and diastolic values in the present study, as opposed to the linear regression method (37), which has the potential for producing negative values for CrCP (24), are more likely reasons for these findings.

**Sustained tilt cerebrovascular responses pre-HDBR.** Over the final 15 min of the tilt before syncope pre-HDBR when the tolerance time was 36 ± 10 min, BP_{MCA} was well maintained until the last minute. In contrast, PET_{CO2}, and CBFV were reduced 5 and 4 min before syncope, respectively. We utilized the two regions based on unchanged vs. changed BP_{MCA} with tilt that may have contributed to a reduction in BPMCA, CBFV, and PET_{CO2} with the two-point method involving the mean and diastolic values in the present study, as opposed to the linear regression method (37), which has the potential for producing negative values for CrCP (24), are more likely reasons for these findings.

**Table 2. Correlation coefficients for linear regression assessing the relationship between BP_{MCA} and PET_{CO2} with CBFV, CrCP, and RAP during the last 5 min before syncope post-HDBR**

<table>
<thead>
<tr>
<th></th>
<th>BP_{MCA}</th>
<th>PET_{CO2}</th>
<th>BP_{MCA}</th>
<th>PET_{CO2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBFV</td>
<td>0.520 ± 0.099 (3)</td>
<td>0.539 (1)</td>
<td>0.680 ± 0.136 (6)</td>
<td>0.613 (1)</td>
</tr>
<tr>
<td>CrCP</td>
<td>0.503 (1)</td>
<td>NS</td>
<td>0.733 ± 0.128 (4)</td>
<td>NS</td>
</tr>
<tr>
<td>RAP</td>
<td>0.622 ± 0.107 (8)</td>
<td>NS</td>
<td>0.803 ± 0.045 (6)</td>
<td>0.645 ± 0.049 (2)</td>
</tr>
</tbody>
</table>

Values are means ± SD of the Pearson product moment correlation (with the no. of individuals out of 8 with significant relationships in parentheses). NS, no significant relationships.
Further investigate relationships between variables. One set of regressions was computed for the period of constant BPMCA (15 to 2 min before syncope), the second set when BPMCA was changing (last 2 min of the test). These analyses confirmed distinct regions over which changes in PETCO\textsubscript{2} or BPMCA were changing (last 2 min of the test). These analyses confirmed BPMCA (shaded line).

\textbf{A}\textsubscript{15} to 2 min before the onset of syncope. Although the direction of change was similar to that described by Carey et al. (5), the timing and potential functional consequences were different, as they found increases in CrCP only during the final 60 s of the test. Conversely, in the present study, CrCP was seen to progressively increase 15 min before syncope and was followed in the final minute by a reduction (see Fig. 3B, noting the inverted scale for CrCP). The increase in CrCP was associated with the reduction in PETCO\textsubscript{2}, whereas the final decrease in CrCP was associated with the rapid decline of BPMCA and is consistent with the reduction in CrCP noted in the early phase of the tilt of the present experiment when BPMCA was reduced from the supine value. Previous work has shown increases in CrCP with reductions in CO\textsubscript{2} (1, 25, 26), with work by Carey et al. (5) suggesting increased CrCP contributes to the development of syncope during the last 60 s of the test. However, this study is the first to suggest increased cerebrovascular tone was associated with a reduction in PETCO\textsubscript{2}, which could contribute to reduced cerebral blood flow with sustained orthostasis 15 min before the onset of syncope. In both the present study and the work presented by Carey et al. (5), sustained orthostasis results in a reduction in diastolic pressure; therefore, the increase in CrCP may lead to closure of cerebral vessels through part of the cardiac cycle, thereby reducing CBFV.

\textbf{Effects of HDBR.} Contrary to the hypothesis that CBFV would show greater reductions post-HDBR, there were no differences in the early phase tilt responses compared with pre-HDBR. A greater reduction in BPMCA may have contributed to the observed reduction in orthostatic tolerance. The potential mechanisms responsible for impaired orthostatic tolerance after HDBR, such as reduced plasma volume noted in this study, have been considered in other research (7, 10, 36). Previous studies investigating cerebral blood flow responses before and after exposure to real or simulated microgravity have shown varied responses. In response to LBNP or assuming a head-up posture, there have been reports of greater reductions in CBFV, potentially indicating an impaired ability to regulate cerebral blood flow (14, 40). However, other work has shown no change in the CBFV response to tilt or LBNP (2, 3) or with rapid deflation of leg cuffs (28). To date, no studies have been conducted examining the potential influences of PETCO\textsubscript{2} or cerebrovascular tone in CBFV responses to orthostasis after HDBR.

Similar to the pre-HDBR results, BPMCA, CrCP, and CBFV decreased over the last 5 min before syncope, but, in contrast, there were no significant changes in CrCP. Post-HDBR, it would appear that changes in BPMCA dominated the cerebrovascular responses, while the effects of PCO\textsubscript{2} and changes in CrCP were not evident with the shorter duration of tilt. These cerebrovascular results suggest that, although orthostatic tolerance was reduced post-HDBR, the reduction does not appear to be the result of altered cerebrovascular hemodynamics, but was related to the more rapid decline in BPMCA.

\textbf{Limitations.} In the present study, PETCO\textsubscript{2} was measured as a surrogate for PACO\textsubscript{2} with the progression toward syncope. The relationship between PETCO\textsubscript{2} and PACO\textsubscript{2} is altered during postural transitions, but it is unknown if the relationship then remains constant with sustained orthostasis (13, 34), since...
further changes in the ventilation-to-perfusion ratio could occur as cardiac output is reduced with prolonged tilt (12).

The use of transcranial Doppler ultrasound for the assessment of cerebral blood flow is dependent on the diameter of the insonated vessel remaining constant. Studies have shown that the diameter of the MCA remains constant with changes in PETCO2, and the application of a mild orthostatic stress (11, 35). However, it is possible that prolonged orthostatic stress and reduced PCO2 could have reduced the MCA diameter so that measures of CBFV might underestimate the decrease in cerebral blood flow. The MCA diameter and cerebrovascular properties might also change with HDBR, as seen in animal models of hindlimb suspension (20, 39), but this seems unlikely with 5 days of HDBR in humans. Regardless, these issues raise a need for caution in interpreting the observed changes in CBFV as alterations in cerebral blood flow.

Perspectives. This study examined the cerebrovascular responses to head-up tilt, with particular emphasis on the contributions of changes in arterial blood pressure and PETCO2, both before and after exposure to 5 days of HDBR. In the early phase of head-up tilt, CBFV was reduced as a consequence of both reduced BPMCA and PETCO2. The dominant change in cerebrovascular properties during this phase was a reduction in CrCP, while RAP was slightly increased. These data contrasted with the proposal that CrCP is related to metabolic factors and should increase as PETCO2 is reduced (5, 27), but are consistent with the recent observations of Stewart et al. (37). As well, RAP is proposed to be predominantly linked to myogenic mechanisms and should have decreased, not increased, with a reduction in BPMCA (27). With sustained tilt, during the period from 15 to 2 min before the onset of syncope, the decrease in PETCO2 progressively increased CrCP though a metabolic mechanism (5, 27), decreasing CBFV with no apparent contribution from BPMCA and RAP. The progressive increase in CrCP might have contributed near syncope to a collapse of cerebral vessels throughout part of the cardiac cycle (5, 33), resulting in reduced CBFV. In the final 2 min before syncope, the rapid decline in BPMCA initiated a myogenic response seen as a reduction in RAP, but this failed to maintain CBFV. Pre-HDBR, the increase in cerebrovascular tone (CrCP), rather than an increase in RAP, contributed to the reduction in cerebral blood flow and eventual development of syncope, whereas, after 5 days of HDBR, orthostatic responses were dominated by the reduction in BPMCA and the actions of cerebrovascular autoregulation. This study revealed the complex interactions of CrCP and RAP in the regulation of CBFV during head-up tilt to presyncope. CrCP responded to myogenic stimuli in the early phase of head-up tilt, and then to metabolic stimuli (PETCO2) as tilt was sustained. In contrast, RAP did not appear to respond to metabolic stimuli and decreased in response to myogenic stimuli only near syncope and not the early period of head-up tilt. Therefore, it would appear that, with prolonged head-up tilt, metabolic factors related to changes in PETCO2, contributed to alterations in cerebrovascular tone and the development of syncope.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS


REFERENCES