Monitoring cerebrovascular pressure reactivity with rheoencephalography

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Abstract. Determining optimal perfusion pressure for patients with traumatic brain injury can be accomplished by monitoring the pressure reactivity index, or PRx, which requires an intracranial pressure monitor. We hypothesized that pressure reactivity could be quantified using a rheoencephalography index, or REGx. We measured the REGx and PRx as repetitive, low-frequency linear correlation between arterial blood pressure and intracranial pressure (PRx) or arterial blood pressure and REG pulse amplitude (REGx) in a piglet model of progressive hypotension. We compared the PRx and REGx against a gold standard determination of the lower limit of autoregulation using laser-Doppler measurements of cortical red cell flux. The PRx produced an accurate metric of vascular reactivity in this cohort, with area under the receiver-operator characteristic curves of 0.91. REGx was moderately correlated to the PRx, (Spearman r = 0.63, p < 0.0001; Bland-Altman bias-0.13). The area under the receiver-operator curve for the REGx was 0.86. Disagreement occurred at extremes of hypotension.

1. Introduction
Traumatic brain injury (TBI) is a major health concern for children in the developed world, and soldiers exposed to blast injury.[1-2] Cerebral perfusion pressure (CPP) management is critical to the outcome of patients with TBI, but there is debate regarding optimal CPP management strategies.[3-5] The latest guideline for management of TBI from The Brain Trauma Foundation endorses the option to individualize management with ancillary monitoring, specifically citing the use of autoregulation monitoring and the pressure reactivity index (PRx).[3,6] The PRx is a low-frequency linear correlation between mean arterial blood pressure (ABP) and intracranial pressure (ICP).[7] In health, the PRx is negative because intracranial blood volume (and therefore ICP) has slow fluctuations which are phase shifted from similar slow fluctuations of ABP. When vascular reactivity is impaired, the PRx is positive because low-frequency intracranial blood volume changes are in phase with ABP changes.[8] Patients with CPP in a range that optimizes the PRx have better outcomes.[6,9]

We seek to evaluate rheoencephalography (REG) as an alternative to ICP measurements for the purpose of monitoring pressure reactivity. Rheoencephalography is the measurement of impedance across the brain, which is a function of the ratio of insulating (fat) and conducting (blood and cerebrospinal fluid) mass.[10,11] Oscillations in the REG signal occur at pulse and respiratory frequencies, thought to be the result of blood volume shifts during hemodynamic cycles. The rate of
change of the REG waveform has been shown to increase with decrements of ABP above the lower limit of autoregulation (LLA), and decrease with decrements of ABP below the LLA.[12] We propose that these changes in the REG waveform are due to vascular resistance changes associated with autoregulatory activity. We therefore hypothesize that slow changes in pulse amplitude of the REG recapitulate similar low-frequency changes in mean ICP. Further, we hypothesized that vascular reactivity can be monitored by correlation of REG pulse amplitude with ABP (REGx). We tested these hypotheses by comparing the REG pulse amplitude with ICP and REGx with PRx.

2. Methods
Hypotension was induced in piglets (5-7 days old, n=9) over 3-4 hours by inflation of a balloon catheter in the inferior vena cava. This method allows for the occurrence of spontaneous slow waves of ABP as hypotension ensues.[13] All animals were monitored with invasive REG (by insertion of stainless steel electrodes 19 mm apart in the right parietal cortex), ICP (by left external ventricular drain), cortical red cell flux (by laser-Doppler), and ABP (by femoral artery catheterization). The standard LLA was determined using plots of laser-Doppler flux as a function of cerebral perfusion pressure according to our previously published method (See figure 1).[13]

The fundamental amplitude of the REG waveform at pulse frequency was calculated and updated every 10 seconds. The ICP waveform was low pass filtered by recording 10 second mean values. This operation removes pulse and respiratory frequency oscillations from the ICP, but preserves slow wave activity, which occurs at periods between 20 and 300 seconds (see figure 2).[7]

PRx and REGx were recorded as a continuous, moving, linear correlation coefficient between 30 samples of mean ICP and mean ABP (PRx) or between the REG pulse frequency fundamental amplitude and mean ABP (REGx), in overlapping 300 second epochs updated every 10 seconds. All values of PRx and REGx were sorted according to the CPP of their calculation interval, binned and averaged in 5 mmHg increments (See figure 3).
3. Results
The PRx and REGx both detected the LLA in this cohort of animals. The REGx was less robust at extremes of hypotension. This is shown in plots of REGx and PRx as a function of CPP normalized to the LLA, with receiver operator characteristics (figure 4).

![Figure 4](image)

**Figure 4** Plots of PRx and REGx (left) as a function of cerebral perfusion pressure (CPP) normalized to the LLA. Values above the LLA are consistently lower than values below the LLA, and this accuracy is quantified with receiver operator characteristics for each index in the right panels (AUC = area under the curve).

Bland-Altman analysis of the PRx and REGx shows that the REGx is slightly biased to a low result (bias = -0.13 when comparing the difference vs. the average), consistent with the low scores seen at extremes of hypotension in Figure 4. Correlation data are shown in figure 5. In this study, the REGx gave the most accurate information at CPP around the LLA.
4. Conclusions

The REGx is a promising modality for measuring cerebrovascular pressure reactivity. The finding that the fundamental amplitude of REG at pulse frequency recapitulates slow waves of ICP is consistent with the hypothesis that pulse amplitude changes in REG are affected by autoregulation-induced changes in cerebral vascular resistance. The REGx has reasonable accuracy for detection of the LLA when compared with a gold standard and good correlation with the PRx. For functional deployment of the modality, non-invasive measurement of the REG should be evaluated.

Disclaimer

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References

[1] Okie S 2005 N. Engl. J. Med. 352 2043-7
[2] Langlois J A, Rutland-Brown W and Thomas K E 2004 Traumatic Brain Injury in the United States: Emergency Department Visits, Hospitalizations, and Deaths. National Center for Injury Prevention & Control (Atlanta, Georgia: US Dept of Health & Human Services)
[3] Brain Trauma Foundation, American Association of Neurological Surgeons, Congress of Neurological Surgeons, Joint Section on Neurotrauma and Critical Care, AANS/CNS. 2007 J Neurotrauma 24 Suppl 1 S59-64
[4] Adelson P D, Bratton S L, Carney N A, et al. 2003 Pediatr. Crit. Care Med. 4 S31-3
[5] Naredi S, Koskinen L O, Grande P O, et al. 2003 Crit. Care Med. 31 2713-4
[6] Steiner L A, Czosnyka M, Piechnik S K, et al. 2002 Crit. Care Med. 30 733-8
[7] Czosnyka M, Smielewski P, Kirkpatrick P, Laing R J, Menon D, Pickard J D 1997 Neurosurgery 41 11,7; discussion 17-9
[8] Lee J K, Kibler K K, Benni P B, et al. 2009 Stroke 40 1820-6
[9] Brady K M, Shaffner D H, Lee J K, et al. 2009 Pediatrics 124 e1205-12
[10] Moskalenko Y E, Kislyakov Y Y, Vainshtein G B, Zelikson B B 1972 Am. Heart J. 83 401-14
[11] Moskalenko Y E, Cooper R, Crow H J, Walter G 1964 Nature 202 159-61
[12] Bodo M, Pearce F J, Baranyi L, Armonda R A 2005 Physiol. Meas. 26 S1-17
[13] Brady K M, Lee J K, Kibler K K, Easley R B, Koehler R C, Shaffner D H 2008 Stroke 39 2531-7