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Optimization of the Coherence Measurement Computed by Means of the Welch Averaged Periodogram Method for Assessment of Impaired Cerebral Autoregulation

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Abstract The coherence method (COH) has been widely used to study the concordance between continuously measured signals intervening in the assessment of cerebral autoregulation in neonates. Several research groups have applied this method to mean arterial blood pressure (MABP) combined with cerebral signals such as the intravascular oxygenation (HbD), cerebral tissue oxygenation (TOI), and regional oxygen saturation (rSO_2) measured by near-infrared spectroscopy (NIRS). All groups contributed in a particular way to the fine-tuning of the application of COH with the Welch averaged periodogram (WAP) method. We have made a comparative study of all published results coupled with an optimization of the use of the WAP method within COH. We have also proposed a pre-processing algorithm to remove signal artefacts, and defined a new critical score value (*CSV*) for COH to distinguish infants with impaired autoregulation from those without.

1 Introduction

Tsuji et al. [1] were the first to use continuously measured NIRS signals to study impaired cerebral autoregulation in neonates over non-successive 30 min epochs. They looked at the concordance between HbD and MABP – reflecting impaired autoregulation – by means of the COH method. If COH was >0.5 the infant was considered to have poor autoregulation. Morren et al. [2] introduced the use of an overlapping sliding window approach dividing the long duration signal into smaller 30 min epochs prior to analysis. They also attempted to maximize the *SNR* of the WAP method. Finally Soul et al. [3] introduced the use of the *CSV* as defined by Taylor et al. [4] applied to the case of impaired autoregulation.

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In this study, we looked at the influences on COH of the signal sample frequency, the parameters intervening in the WAP method, and the frequency band of interest. Furthermore, we developed a new method to fix the *CSV*, based on the calibration of the mean COH score on the mean absolute-valued correlation coefficient (COR) score, which allows us to use the value 0.5 as the threshold above which a patient is said to have impaired autoregulation. Finally we developed a pre-processing algorithm to remove signal artefacts.

2 Datasets

All mathematics were developed for and applied on preterm infants from the University Hospital Zurich (Switzerland), the University Medical Centre Utrecht (The Netherlands), and the University Hospital Leuven (Belgium). SaO_2 was measured continuously by pulse oximetry, and MABP by an indwelling arterial catheter. Transcranial NIRS signals HbD (measured by the Critikon Cerebral Oxygenation Monitor 2001), rSO_2 (INVOS4100, Somanetics), and TOI (NIRO300, Hamamatsu) were measured for non-invasive monitoring of cerebral oxygenation. All signals were measured simultaneously in the first days of life, and recorded at the frequency of 0.333 Hz (periodicity = 3 s).

3 Methods

The first constraints concern the signal sample frequency (f_s) and the frequency band of interest. Urlesberger et al. [5] and later von Siebenthal et al. [6] showed that the measured NIRS signals could have a cyclic duration of as little as 10 s. Because of the use of the fast Fourier transform (FFT), the *Nyquist theorem of digital sampling* means the sampling frequency must be at least twice the smallest signal intrinsic frequency, i.e. at least 0.2 Hz ($f_s \geq 0.2$ Hz). von Siebenthal et al. [6] also showed that MABP fluctuates with a periodicity of 60–150 s (cut-off frequency $f_{cut} \geq 0.0067$ Hz). MABP being the most influential signal of all those considered, we studied impaired autoregulation in the periodicity band 25–300 s [3].

The continuously recorded signals were divided into epochs of a shorter duration beforehand, allowing us to have a continuous assessment of impaired autoregulation [2]. For this reason we called them calculation epochs (*C-epochs*), of duration *TC* (min). The WAP method computes an averaged frequency spectrum of the signal on each of these C-epochs. The average is performed on the basis of N smaller overlapping epochs into which each C-epoch is divided. We called these smaller epochs *H-epochs* as they apply a highpass (time-domain) filtering on the signals. The duration of a H-epoch

(*TH*, min) should be at least one cycle of the signal periodicity ($TH \geq 2.5$ min). To ensure the last H-epoch contained in a C-epoch is not cropped (which would mean that the signal is again highpass filtered), we could demonstrate:

$$N = \frac{TC - TH_{Over}}{TH - TH_{Over}} \tag{1}$$

where TH_{Over} (min) is the overlap width between two successive H-epochs. As it was not certain we included an integer number of signal cycles in each H-window, we applied a *Hanning window* to each H-epoch to avoid the leakage phenomenon when using the FFT. Notice that no Hanning windowing was applied to the C-epochs, as it generated an artefact in the low frequencies of the COH spectrum. Carter et al. [7] showed the H-epochs should be half-overlapped in the case of the application of Hanning windowing ($TH_{Over} = TH/2$). On the other hand, we found that the higher the value of N (the higher the *SNR*), the lower the amplitude of COH. Thus, by choosing a different N, we obtained different COH values. Eq. 1 became:

$$TC = \frac{TH(N+1)}{2} \tag{2}$$

The duration of the C-epochs in which the full-length signals are originally divided may – ideally seen – not be chosen. We also found that the ratio TH/TC should be in the range of 0.5 or smaller ($TH \leq TC/2$) otherwise there is no sense in applying the WAP method as the H-epoch duration tends to the C-epoch one.

In 1998, Taylor et al. [4] found that the amplitude of COH was influenced by the parameters intervening in the WAP method. To distinguish patients demonstrating a concordance between the two signals investigated from those with no concordance, they set up a new *CSV* definition computed from *TC*, *TH*, and a *F*-hypothesis test. However this definition did not take into account the influence of TH_{Over} intervening in Eq. 1. Therefore we have proposed a new methodology: adapt N until the mean COH – on all infants from the same medical centre – equals the mean absolute-valued (for comparability with COH) COR, the *CSV* of COR being per definition 0.5. Making N variable changes only the *SNR* of the frequency spectrum and does not affect the signals. The sole free parameter in Eq. 2 is *TH*, in that it fulfils some conditions. We chose *TH* to be equal to 5 min in accordance with the work of Soul et al. Table 1 presents the summary of the parameter values used by all working groups, to which we added those of Wong et al. [8].

Finally, we have also developed a pre-processing stage to remove measurement artefacts induced by medical interferences and by the conversion between analogue and digital data. Each artefact point in a signal was simultaneously

Table 1 The following is a summary of all parameters intervening in the Welch averaged periodogram method applied by Tsuji et al. (2000), Morren et al. (2001), Soul et al. (2007), and Wong et al. (2008)

	Tsuji et al.	Morren et al.	Soul et al.	Wong et al.
f_s	2 Hz (0.2 Hz)	6 Hz (0.2 Hz)	2 Hz (0.4 Hz)	1 Hz
f_{cut}	0.01 Hz	0.01 Hz	0.04 Hz	0.02 Hz
TH	–	12 min	5 min	10 min
TH_{Over}	–	11 min 55 s	2.5 min	7.5 min
N	–	217	3	5
TC	30	30	10	20
TH/TC	–	0.4	0.5	0.5
TC_{Over}	–	10	0	0
CSV	0.5	0.5	0.77	0.5

deleted in all other signals, as done by Soul et al. for artefacts lasting more than 1.5 s. The steps of the algorithm we developed are:

1. Remove artefact-like repetitive points included in the recordings.
2. Keep the signals in normal physiological ranges, particularly SaO_2 in the range 80–100%.
3. Divide the signals in non overlapping 10-min epochs, from each of which we kept only the portions belonging to interval $[median - IQR, median + IQR]$.
4. As this is not enough to detect some extra peak artefacts of longer duration contained in MABP and SaO_2 (the two most influential signals), centre and absolute-value MABP (and afterwards SaO_2) (result 1), and on the other side differentiate, square, and reduce it (result 2) with the aim of emphasizing the signal extremes. Result 1 gives an average peak amplitude, and result 2 acts as a ponderation coefficient with value close to 1 at peak abscises. Finally, multiply together the obtained signals, which indicates which signal points may be deleted.

4 Results

There are about 55% repetitive points for the INVOS, 45% for the Critikon, and 15% for the NIRO spectrometers. They were all removed prior to application of pre-processing steps 2 to 4 which themselves delete about 60% of the data. Steps 2 to 4 are very effective: values of COH and COR are significantly higher than without pre-processing. Fig. 1 illustrates an example of pre-processed data. The optimized values of TC (N) for the Zurich, Leuven, and Utrecht data are 10 min (3), 12.5 min (4), and 15 min (5). The CSV computation of Taylor et al. [4] generates high values (around 0.7) in the case of measured NIRS signals, only affordable with a low N, i.e. a low SNR.

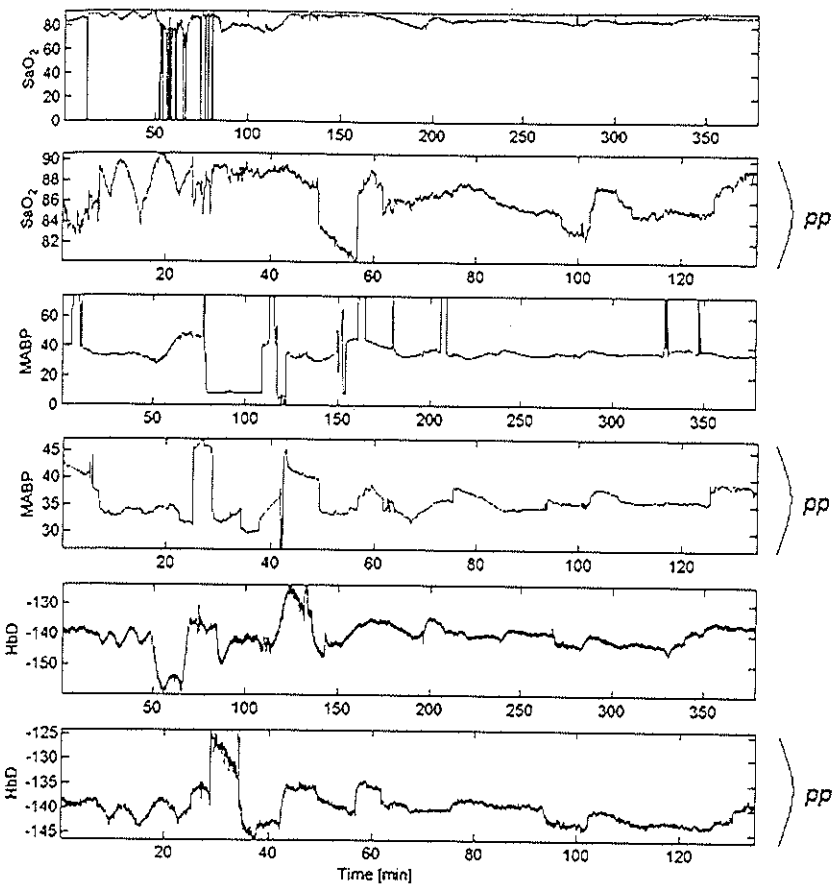

Fig. 1 Illustration of the efficiency of the preprocessing algorithm applied to SaO_2, MABP, and $HbD/rSO_2/TOI$. The figure shows original and preprocessed (*pp*) signals measured in the University Hospital Zurich (Switzerland) by the Critikon Cerebral Oxygenation Monitor 2001. Most of the artefacts due to medical interferences and patient handling were removed. Although efficient, the preprocessing makes the signals very short and damages their frequency content

5 Discussion

The repetitive points in the data prior to analysis may be due to the conversion from analogue to digital data, to the spectrometer resolution and some simply to the sometimes constant nature of the signals. This step in the pre-processing of the data, however, is not needed as we discovered that the repetitive points are equally distributed all along the recording. The pre-processing otherwise has a bad influence on the frequency content of the signals. We should

complementarily set up an *intelligent interpolation* for artefacts lasting more than 1.5 s otherwise we break the signal periodicities. The pre-processing also makes the recording much shorter in duration, with the risk that it becomes impossible to analyse by means of a sliding-window approach.

With regard to the WAP method, the FFT assumes the signals to be periodic: we assume this periodicity in line with the works of von Siebenthal et al. [6] and Urlesberger et al. [5]. The decrease in the coherence amplitude with increasing N should thus actually not occur, because between one H-epoch and another the extremes in the frequency spectrum of COH should occur at the same frequencies.

Finally, working with a *CSV* of COH equal to 0.5 suggests a relation between two signals based on 50% shared variance, which can be defended. But this *CSV* should ideally be determined empirically from the patient clinical characteristics and outcomes, or statistically in the way done by Taylor et al. [4]. With the *CSV* fixation we have proposed, the amplitude of COH is in the range of COR which allows comparability of these two complementary methods. The *CSV* definition of Taylor et al. [4] generates high values in the case of detection of impaired cerebral autoregulation, but could perhaps be used in other applications (e.g. for cardiologic data).

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