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The frequency domain versus time domain methods for processing of intracranial pressure (ICP) signals

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Abstract

Two methods for analyzing intracranial pressure (ICP) waveforms were compared. The frequency domain (FD) method converts the signal from the time domain to the frequency domain by a fast Fourier transform (FFT), while the time domain (TD) method calculates peak-to-peak value of the pulse waveform directly from the time samples. First, the ICP signal was regenerated from the first harmonic of the FFT and compared against the time domain raw ICP signal. We found that the FD method may underestimate pulse amplitude if there is heart rate variability or a high harmonic distortion. Second, to explore the significance in a larger data set, differences between FD- and TD-derived pulse amplitudes were determined for a total of 50,978 6-s time windows of 79 head injury patients. The mean difference in pulse pressure amplitude was 2.9 mmHg for the 50,978 6-s time windows. Differences between TD- and FD-derived pulse amplitudes were $\geq$2.0 mmHg in 58.8% of the 50,978 time windows. In about 33% of time windows FD amplitudes were <2 mmHg when TD amplitudes were $\geq$4 mmHg, and vice versa. Hence, the TD method is superior to the FD method for calculation of pulse amplitudes. Nevertheless, in this material both the TD and FD methods revealed significantly elevated pulse amplitudes in head injury patients with bad outcome (i.e. Glasgow Outcome Score 1–3).

Keywords: Intracranial pressure; ICP waveform analysis; Fast Fourier transformation; Time domain method; Frequency domain method

1. Introduction

Continuous intracranial pressure (ICP) monitoring has an important role in management of head injury patients [1]. Waveform analysis may provide information about intracranial compensatory reserve capacity (i.e. intracranial compliance) [2,3] and the clinical course following head injury [1,4].

Time domain analysis of the ICP waveform was used in the 1970s, e.g. the peak-to-peak pulse pressure amplitude was calculated after filtering of slower components (respiratory and B-waves) [2]. Since the 1980s the most common way of analyzing ICP waveforms has been to convert the signal to the frequency domain (FD) by a fast Fourier transform (FFT) and extract parameters such as the root-mean-square (rms) amplitude of the fundamental harmonic [3,5,6]. An underlying, but often unstated assumption is that the ICP signal deviates little from a pure sinusoid, i.e. that the distortion factor is low and that most of the energy remains in the fundamental harmonic. Another assumption is that the signal is stationary over the analysis window, i.e. statistical properties should not change much. This ensures that there is a single fundamental peak in the frequency spectrum.

Since ICP monitoring is used in surveillance of patients with brain damage it is particularly important to explore how different methods for ICP analysis may affect the analysis results. This study explored whether significant information about the ICP waveform in head injury patients can be lost when using the Fourier-based FD method, as compared to extracting morphological data directly from the time domain signal [7].

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2. Material and methods

2.1. The frequency domain (FD) method

The first step of the frequency domain method is to estimate the power spectrum of the ICP signal in the bandwidth from zero to half the sampling frequency by means of an FFT-based method [5,6].

Starting with the input samples $x[n]$, $n = 0, \ldots, N-1$ typically sampled over 6 s, a Discrete Fourier Transform (DFT) of length $M \geq N$ assuming that $x[n]$ has been zero-padded for $k = N, \ldots, M-1$ is performed (Eq. (1)).

$$X[k] = \sum_{n=0}^{M-1} x[n]\, \mathrm{e}^{-\mathrm{j}2\pi nk/M}, \quad k = 0, \ldots, M-1 \tag{1}$$

M is typically a power of 2 (1024, 2048, ...) so that an FFT-algorithm can be used for computing the DFT efficiently. Although, the zero padding does not increase the resolution of the estimator, it interpolates the frequency spectrum so that a high accuracy is achieved in extracting the frequency of the first harmonic. This is mathematically similar to the direct interpolation method that interpolates with the same accuracy as if $N = 32$ samples had been zero-padded to $M = 3200$ before Fourier transformation [5]. The magnitude spectrum usually has distinct peaks that are harmonics of each other; the largest peak at index $k = k_1$ usually corresponds to the heart rate and is the peak that is of interest for further analysis. The example shown in Fig. 1a and b is a case which fit this model particularly well.

Our analysis has been done over fixed time intervals. This is the standard way in the literatures [8,9], although there are cases where the analysis interval has been synchronized with the heart rate and is an integer number of single waves. This is easiest to accomplish when an electrocardiogram (ECG) signal is available, as in [9] and was not attempted in our study.

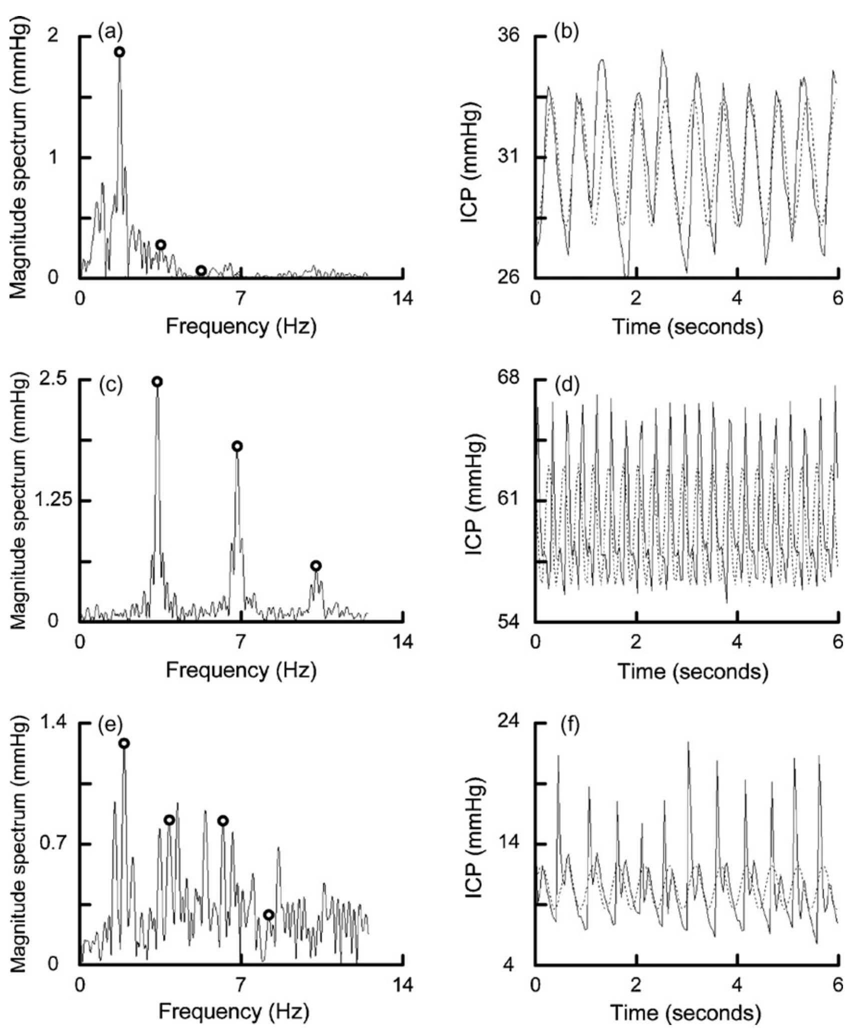

Fig. 1. For three different 6-s time windows are shown the FFT magnitude spectrum with its first identified peaks; the first harmonic being the largest peak to the left (a), (c) and (e). The corresponding ICP raw signal (continuous line) superimposed on the ICP signal regenerated from the FFT-derived first harmonic (interrupted line) are shown in (b), (d) and (f).