Time-frequency analysis of the electrocortical activity during maturation using wavelet transform

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Abstract. In this study, we introduce the wavelet transform (WT) as a method for characterizing the maturational changes in electrocortical activity in 24 fetal lambs ranging from 110–144 days gestation (term 145 days). The WT, based on multiresolution signal decomposition, is free of assumptions regarding the characteristics of the signal. The approximation of the electrocortical activity at resolutions varying from $2^{-i+1}$ to $2^j$ can be extracted by decomposing the signal on a wavelet orthonormal basis of $L^2(\mathbb{R})$. We performed multiresolution decomposition for four sets of parameters $D_{2^j}$, where $-1 < j < -4$. The four series WT represent the detail signal bandwidth: (1) 16–32 Hz, (2) 8–16 Hz, (3) 4–8 Hz, (4) 2–4 Hz. The data were divided into three groups according to gestational age: 110–122 days (early), 123–135 days (middle), and 136–144 days (late). In the early group, the power was highest in the fourth signal bandwidth, with relatively low power in the other bands. Increase in gestational age was characterized by increased power in all four bandwidths. Comparison of the cumulative distribution function of the power in the four wavelet bands confirmed the presence of two statistically different patterns in all three age groups. These two patterns correspond to the visually identified patterns of HVSA (high-voltage slow activity) and LVFA (low-voltage fast activity). The earliest development change occurred in HVSA, with progressive increase in power in the 2–8 Hz band. Later changes occurred in LVFA, with a significant increase in power in the 16–32 Hz band. The same database was also analyzed by the short-term Fourier transform (STFT) method, the most common time-frequency analysis method. Comparison of the results clearly show that the WT provided much better time-frequency resolution than the STFT method and was superior in demonstrating maturational changes in electrocortical activity.

1 Introduction

The electrocorticogram (ECoG) has frequently been used as measure of central nervous system (CNS) function. Electrocortical activity can be detected in the fetus as early as the second trimester and has been shown to undergo maturational changes throughout late gestation. Visual analysis of the ECoG obtained in fetal lambs suggested a progression from an immature pattern of low amplitude and variable frequency to a mature cyclic pattern characterized by alternating periods of high-voltage slow activity (HVSA) and low-voltage fast activity (LVFA) (Ruckebusch 1972; Szeto and Hinman 1985). The timing of the transition from an immature pattern to a mature pattern was found to be variable, but the two ECoG patterns could be distinguished visually as early as early 115 days of gestation (term 145 days). After that, the fetal ECoG alternates between HVSA and LVFA, with cycle durations of 10 min (Szeto and Hinman 1985). A progressive increase in cycle duration has been reported throughout the third trimester (Szeto and Hinman 1985). The application of fast Fourier transform (FFT) to the ECoG has provided some quantitative information of the maturational process involved (Szeto et al. 1985). The predominant distribution of power during HVSA was found to be lower than 4 Hz. The progression from HVSA to LVFA appeared to be due to both a decrease in power density in the 0.3–3 Hz band and an acquisition of power in the faster frequencies (greater than 12 Hz). Maturational changes were found to occur primarily in the LVFA episodes, with no significant change in the power spectrum of the HVSA episodes. An increase in gestational age was associated with a decrease in relative power density in the 0.3–3 Hz band and an increase in relative power density in the 15–30 Hz band. Furthermore, there was an increase in the maximal frequency detected as a function of gestational age. This age-related increase in frequency was confirmed in a subsequent study using spectral analysis (Szeto 1990). Spectral analysis techniques, however, were unable to identify the two
distinct ECoG patterns until 122-125 days of gestation, even though the two patterns were clearly apparent by 115 days using visual analysis. This discrepancy may reflect the limitations of the FFT.

Although the FFT has been widely used in applications from pattern recognition to image processing, it suffers from several limitations (Grossman and Morlet 1984; Daubechies 1988; Mallat 1989). In the FFT method, a signal in the time domain is translated by the FT into a signal in the frequency domain. The FT expands the original signal in terms of orthonormal basis functions of sine and cosine waves. The Fourier coefficients of the transform function represent the contribution of each sine and cosine wave at each frequency. The underlying assumption in the FFT method is that the original time domain signal is periodic in nature. As a result, the FT has difficulty with signals that are transient components which are localized in time (Grossman and Morlet 1984; Daubechies 1988; Mallat 1989).

The FFT has been used extensively for the analysis of biomedical signals despite its requirement of stationarity. To satisfy this requirement, investigators mostly employ FFT using short epochs while performing long-term signal monitoring (short-time Fourier transform, STFT). The use of a single size analysis window smears the power of the signal across the time-frequency plane and fails to represent the signal adequately (Grossman and Morlet 1984; Daubechies 1988; Mallat 1989). The spectral resolution of the STFT method can be improved with the use of a longer data window. However, using a long window to improve the spectral resolution risks compromising the assumption of stationarity in the chosen window. Choosing a short window produces low spectral resolution. The other disadvantage of the classical FT is the leakage of the main lobe in the power spectrum into the sidelobes in the analysis window (Daubechies 1990; Mallat 1989; Chui 1992). In recent years, a new family of orthonormal basis function has been proposed and used that lead to transforms which overcome the problem of the FT. These basis functions are called wavelets (Grossman and Morlet 1984; Daubechies 1988; Mallat 1989) and are discussed in Methods.

Little is known about the characteristics of the ECoG signal during maturation, both in the time and frequency domains. The purpose of this study was to characterize the ECoG signal by determining how the signal changes in the frequency domain during maturation. Here we introduce the wavelet transform (WT) method to analyze the ECoG fluctuations. The WT is based on multiresolution signal decompositions and thus is free of assumptions regarding the characteristics of the signal and is able to localize the nonstationary signal more accurately (in both the time and frequency domains) than the STFT (Grossman and Morlet 1984; Daubechies 1988; Mallat 1989; Rioul and Vetterli 1991; Chui 1992; Hlawatsch and Boedreaux-Barletes 1992). This time and frequency localization can be achieved by the WT since it uses short windows at higher frequencies and long windows at low frequencies. However, the classical methods such as the STFT uses a single size analysis window. This method smears the energy of the signal across the time-frequency plane. As a result, the WT shows better time and frequency resolution than other time-frequency methods, especially for the analysis of nonstationary signals, as in the case of the analysis of ECoG for a long period.

The WT has been successfully used in analyzing biomedical signals (Kronland-Martinet et al. 1987; Kronland-Martinet 1988; Meste et al. 1989; Akay et al. 1992; Healy and Weaver 1992; Yang et al. 1992). The sound produced by turbulence caused by occluded arteries in dogs was measured and analyzed using the WT. Accurate and reliable time and frequency localizations were obtained. A direct correlation between blood flow and sounds due to turbulence was observed in the time and frequency domains (Akay et al. 1992). In another application, ventricular late potentials were detected by using 16 beats without any preliminary filtering (Meste et al. 1989). The WT was used in magnetic resonance imaging and was found to be more reliable and accurate than the traditional FT (Healy and Weaver 1992). In addition, the WT was applied to the heart rate fluctuations obtained from five patients undergoing carotid endarterectomy for 5 h before and 3 h after declamping. Recently, the WT was introduced to analyze the heart rate variability during carotid surgery (Akay et al. 1993a; Akay and Welkowitz 1993).

In this study, the WT was applied to the ECoG signal obtained from 24 fetal lambs at different stages of gestation. We also applied the STFT to the same database, and the results were compared to those obtained with the WT. Preliminary data from this study have already been presented (Akay et al. 1993b).

2 Methods

2.1 Experimental procedure

Twenty-four fetal lambs were surgically instrumented for chronic intrauterine recording of electrocortical activity between 98 and 120 days of gestation, in accordance with guidelines approved by the Institution for the Care and Use of Animals. Details of the surgical procedure have been described previously (Szeto et al. 1985). Briefly, four stainless steel screws (size 0-80) were implanted over the parietal cortex for recording ECoG activity. In addition, a polyvinyl catheter was placed in the distal aorta to permit collection of arterial blood for blood gas determinations. Intraoperatively, 2 g of ampicillin was placed in the amniotic cavity and 1 g in the peritoneal cavity of the ewe (Szeto et al. 1985).

2.2 Recording procedures

Ewes were allowed at least 72 h to recover after surgery before ECoG recording (Szeto et al. 1985). Polygraphic recordings were obtained with the ewe standing or lying quietly in a cart. The ewe had free access to food and water throughout the recording period. The 1st h of recording was considered the habituation period, and data recorded during the 1st h were not used in this