Neonatal EEG Audification for Seizure Detection

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Abstract— **Technologies for automated detection of neonatal seizures are gradually moving towards cot-side implementation. The aim of this paper is to present an alternative way to visualize the output of a neonatal seizure detection algorithm. For this purpose audified neonatal EEG is considered. The EEG is audified with the aid of the neonatal seizure detection algorithm which selects the representative channels for stereo audio image and controls the signal gain. A survey on the usefulness and accuracy of the presented audification method has been performed. The results of the audification method compare favourably to that of using amplitude integrated EEG for detection of neonatal seizures.**

I. INTRODUCTION

Neonatal seizures are the most common neurological emergency in the neonate and are a serious concern for clinicians and parents worldwide [1]. Only about one third of all neonatal seizures are clinically visible and many remain undetected in the busy Neonatal Intensive Care Unit (NICU) environment. The only method available to detect all neonatal seizures accurately is continuous multi-channel EEG monitoring. Interpretation of neonatal EEG requires a neurophysiologist or paediatric neurologist with specific expertise in neonatal EEG. This expertise is not available on a 24h basis, 7 days a week. To fill the gap in the availability of appropriate expertise, clinical staff in the NICU are using a simpler form of EEG monitoring, called amplitude integrated EEG or aEEG [2]. Amplitude integrated EEG is a logarithmically-scaled, temporally-smoothed and compressed display of EEG which is usually computed from two EEG channels, one from each hemisphere. Despite the fact that many short and focal neonatal seizures are undetectable with aEEG and interobserver agreement is poor [3], aEEG currently serves as a trade-off between very inaccurate clinical detection of seizures and very accurate but scarcely available neurophysiologic expertise, and thus is widely adopted worldwide in the NICU.

As an alternative to aEEG usage, many groups in the world are working to develop algorithms for automated detection of neonatal seizures on continuous multi-channel EEG. An automated decision support system that could detect and annotate seizures on the neonatal EEG would be extremely useful for clinicians in the NICU. A number of methods have been previously proposed but to date their transition to clinical use has been limited due to: (i) The proof of concept nature of the work performed, which involved carefully selected short-duration EEG segments [4]. (ii) An unrealistic validation regime such as testing on training data or excluding the worst performing records [5]. (iii) The provision of algorithm performance which is currently unacceptable in a clinical setting [6].

Our group has recently developed, validated and patented an accurate and robust real-time neonatal seizure detection system [7-9]. In this study, neonatal EEG is audified with the aid of the probabilistic output of an automated neonatal seizure detector. A survey of over 1 hour was designed in order to compare the accuracy of detecting seizures by means of aEEG with the accuracy of detecting seizures with audified EEG. Fourteen people including five neonatologists with experience in interpreting the cotside EEG from the second largest maternity hospital in Europe, Cork University Maternity Hospital (CUMH) were surveyed and the survey results are reported in this work.

II. NEONATAL SEIZURE DETECTION

A. *Amplitude-integrated EEG*

The amplitude-integrated EEG is widely used in NICUs. There have been numerous studies that report low sensitivity of aEEG for neonatal seizure detection and its inappropriateness for usage in the neonatal population in general [3, 10]. Technically, the filtered EEG signal is first rectified. The amplitudes are then smoothed using a moving average filter and the final result is plotted on a semi-logarithmic scale which is linear from 0 to 10 mV, and logarithmic from 10 to 100 mV. The aEEG emphasizes the amplitude of the EEG signal. Interpretation of aEEG is primarily based on pattern recognition and experience of the user is important. The maximum and minimum peak-to-peak amplitudes of the EEG signal are displayed to indicate the variance in aEEG amplitudes. Typically, an increase in the lower border of the aEEG trace is representative of seizures as shown in Fig. 1 (a).

B. *Algorithm for Neonatal Seizure Detection*

The developed automated neonatal seizure detection system has been described in detail in [8, 11]. A video EEG machine is used to record multi-channel EEG using the 10-20 system of electrode placement modified for neonates. The following 8 EEG channels in bipolar pair are used to feed the EEG data into the system: F4-C4, C4-O2, F3-C3, C3-O1,

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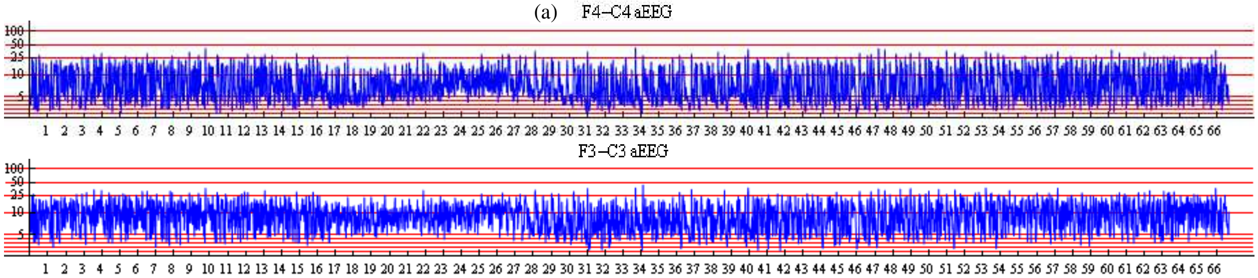

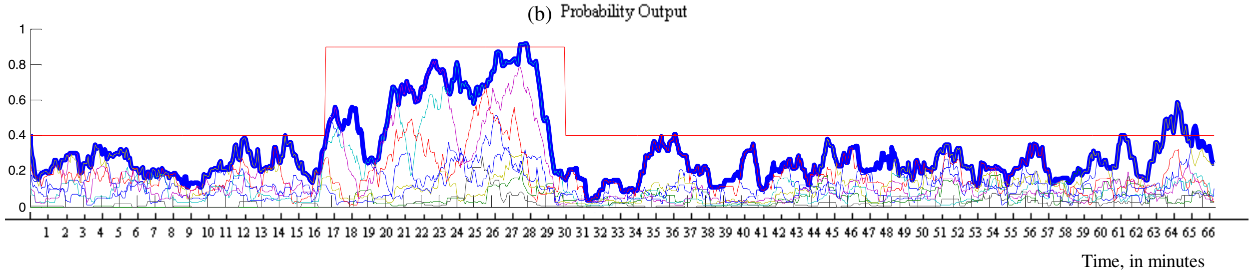

Figure 1 Example of visualization of the output of the neonatal seizure detection system for 66 min of EEG. Plot (a) indicates aEEG channels, plot (b) – probabilistic output for each channel with the maximum probabilistic output across channel (in bold). Seizure onset and offset are annotated as 16 min 37 s – 30 min 5 s and superimposed on top in plot (b) in red.

T4-C4, C4-Cz, Cz-C3 and C3-T3. The EEG from the 8 channels is downsampled to 32Hz with an anti-aliasing filter set at 12.8Hz. The EEG from each channel is then split into 8s epochs with 50% overlap between epochs. A long feature vector which consists of fifty-five features is extracted from each epoch. The features are designed to convey time and frequency domain characteristics as well as information theory based parameters. The features are normalised by the saved normalization template (subtracting the mean and dividing by the standard deviation which were computed from the training data). A support vector machine classifier is applied separately to each channel of the testing data. The output of the SVM is converted to probability-like values with a sigmoid function. The probabilistic output is then time-wise smoothed with a moving average filter. Thus, the output of the seizure detection algorithm is a probabilistic trace for each EEG channel as shown in Fig. 1 (b).

III. AUDIFICATION OF EEG

It is believed that human hearing input is better than the visual input when it comes to assessing both the spatial and temporal evolution of the frequency characteristics of a signal. Hearing is flexible and low-cost. It allows for faster processing than visual presentation, it has better temporal resolution, and represents an additional information channel, releasing visual sense for other tasks.

Human EEG has previously been audified for a variety of purposes [12-15]. In [12], the detection of epilepsy in adults was performed with audified EEG. The recorded frequencies were lifted into the human audible range, by saving the original waveform with higher sampling rate. With signal re-sampling, time and pitch manipulations are always linked so that time compression scales pitches upwards, time stretching scales pitches downwards. The same procedure is used in [13] for listening to sleep EEG recordings. The resultant audio sounds noisy and real-time EEG playback is obviously not possible by using this method.

Another approach is to map the EEG spectral frequencies to the audible range by sonification [14]. Sonification is a data-driven sound synthesis, in which the dominant EEG frequencies are extracted using the FFT transform and then tones of the mapped frequencies are created with pre-specified duration, pitch, etc. With sonification, the activity in a specific spectral band can be monitored and real-time playback is possible. Model-based sonification of adult EEG has been described in [15]. A set of differential equations is used to drive audio synthesis from the EEG signal. With the sonification approach what is heard is not the real EEG but rather the 'synthetic' artificially generated audio waveforms which are guided by the original EEG content.

In contrast to the approaches described above, the approach to audify neonatal EEG in this work is based on:

- The phase vocoder which allows for pitch scaling without affecting the signal duration
- Stereo audio with left/right channels representing left-right hemispheres
- The selection of the left and right EEG channels, and their signal gain is guided by the multi-channel neonatal EEG seizure detector

The process is outlined in Fig. 2 with an example of 1000s of EEG as an input. First, the same pre-processing steps are applied to EEG as in the seizure detector. Then, the EEG is passed through the phase vocoder [16, Appendix A] to change the temporal characteristics of a signal while retaining its short-time spectral characteristics. This process intuitively corresponds to stretching the time-base of a signal spectrogram. The signal sampled with 32 Hz is thus slowed down by a factor of 100 by the phase vocoder. It is then resampled at 32 kHz sampling rate. This corresponds to the

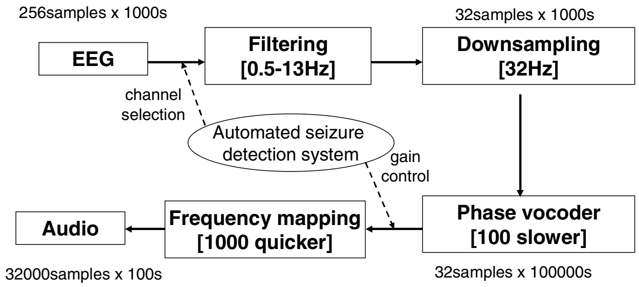

Figure 2. A flowchart for audification of 1000s of neonatal EEG.

pitch shifting from the original range of [0.5-13] Hz to the new range of [0.5-13] kHz so that the most dominant frequencies of seizure [0.5-6] Hz are mapped to the most sensible audible range, in particular to the range of human scream [3-4] kHz. This EEG audification technique allows for speeding up the EEG real-time play-back, in our case by a factor of 10 allowing 1 hour of EEG to be played in roughly 6 minutes.

The resultant audio signal is made stereo, with left/right channels corresponding to left/right brain hemispheres. The automated seizure detection algorithm is used to select a channel from each hemisphere. In particular, the cumulative seizure probability is computed from the per-channel probabilistic outputs which are shown in Fig. 1 (b). The channels with the maximum cumulative probability is taken separately from the left (F3-C3, C3-O1, Cz-C3, C3-T3) and right hemisphere (F4-C4, C4-O2, T4-C4, C4-Cz).

Additionally, the signal gain is multiplied by the maximum probabilistic output of the system which is shown in Fig. 1 (b) in bold. This allows for making EEG segments which are likely to be seizures louder than the background.

IV. SURVEY DESIGN AND RESULTS

The survey was organized as follows. Eleven 1h 8-channel EEG segments were selected from the database of continuous neonatal EEG [8]. For each EEG segment, aEEG was computed which represents current clinical practice. Additionally, the probabilistic output of the seizure detection system was obtained and used to audify the EEG as described in the previous section. Two examples, one with no seizures and the other with a single clear 5-min-long seizure in the middle, were used for quick training purposes to allow the audience to get used to the typical sound of seizure and background EEG. The remaining 9 examples were used for testing. All examples of audified neonatal EEG used in the survey can be found online, http://rennes.ucc.ie/~andreyt/visual/. The audified EEG output was accompanied by the corresponding aEEG traces. The 11 EEG segments (2 for training and 9 for testing) were taken from 11 different patients. Each segment consisted of ~6 minutes of audio which represent one hour of EEG. For every testing example, the audience was asked to provide time onset and offset of every detected seizure.

Fourteen people participated in the survey. Among them there were 5 neonatologists with experience in interpreting EEG. Their opinions are most valuable and are used here to score the accuracy of aEEG. Neither neonatal clinicians nor other surveyed users had any experience in listening to audified EEG (some however have 'listened' to old paper-based EEG machines). For this reason, the results of audified EEG presented here are obtained from the whole surveyed audience.

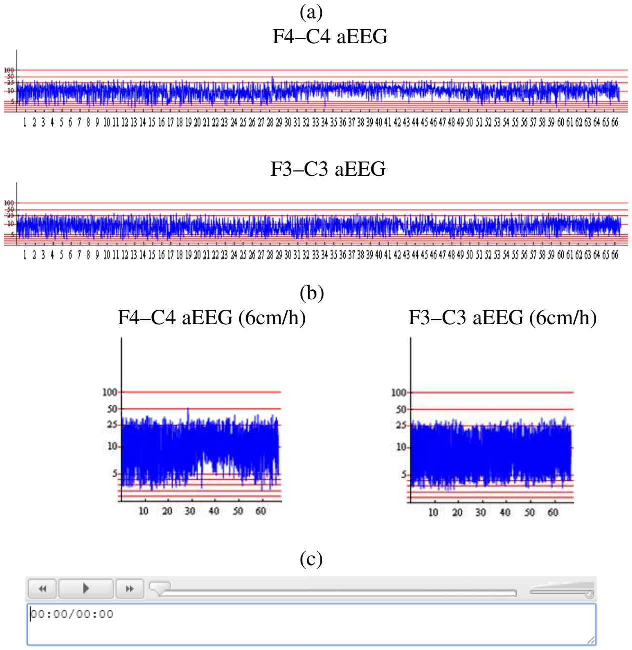

Figure 3. Survey design. Plot (a) shows the aEEG traces for 2 channels. Plot (b) shows the aEEG traces using the conventional aEEG display of 6cm per hour. Plot (c) shows the web-interface which enables a user to play the audified EEG and insert the perceived seizure onsets and offsets. Plots (a) and (b) are used to assess the performance of aEEG. Plots (b) and (c) are used to assess the performance of audified EEG.

The results of the survey are summarised in Fig. 4 for the epoch-based sensitivity and specificity metrics. The 'Sys Prob' curve (probabilistic system output) indicates the performance of the system itself on the chosen examples. The other points, 'Clin aEEG' and 'Clin aEEG + Aud' indicate the performance achieved by the surveyed audience using aEEG alone and aEEG + audified EEG, respectively.

It can be seen that the performance achieved with aEEG alone conforms to what has been previously reported. Sensitivity of 38% and specificity of 92% using aEEG were reported in [3]. Sensitivity of 12%–38% has been reported in [17]. It can also be observed from Fig. 4 that the results of using audified EEG are better than using aEEG. It has been observed that certain seizure morphologies resulted in a very distinct pitch-rising sound. The audification technique provided similarly low sensitivity which indicates that not all seizures resulted in this sound. However, this clearly audible phenomenon was seen to be solely specific to seizures as indicated by its specificity which is by far larger than for the aEEG method.

It is worth noting that the location of the points which resulted from the survey should be compared to each other rather than to the system performance curve. The curve of system performance per se depends on the complexity of the

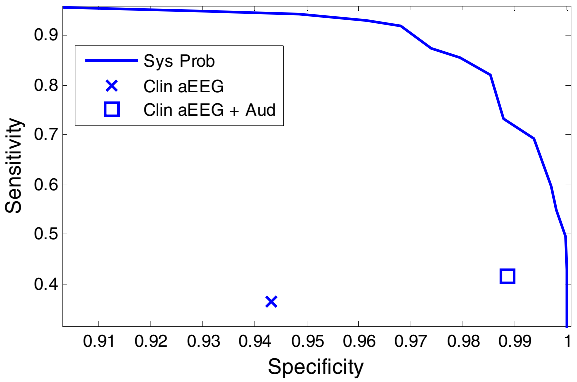

Figure 4. The results of the survey.

9 chosen testing examples. In this study, the system performance equals to 98% of AUC, which is larger than the AUC of 95-97% previously reported for the same system [8, 9]. This left little space for the surveyed audience to improve over the system results.

The results of the survey indicate that the developed neonatal seizure detector with its current level of performance would unambiguously be of benefit to clinicians as a decision support tool. Using the EEG audification combined with the probabilistic output of the seizure detector as an alternative to visualization methods has a potential to increase the neonatal seizure detection rate in clinical practice.

The same technique has been used to audify background EEG of preterm newborns as young as 24 weeks of gestational age and the demo of the baby brain music can be found at http://youtu.be/IQqNELoDwkI.

APPENDIX A

The phase vocoder consists of 3 main parts; analysis, processing, and synthesis, as shown in Fig. 5. i) Analysis: The signal is segmented into overlapping frames and the short-time Fourier transform is applied to each frame. ii) Processing: The magnitude and phase are separated. The phase, which is measured modulo 2π, is unwrapped by keeping track of cumulative phase variation. The phase difference between the two successive frames is used to estimate the instantaneous frequency. In order to achieve time-scale modifications, the instantaneous frequency is integrated to form a phase function, which can be decimated or interpolated to the new time scale. In this manner, the magnitudes of the original spectrum are used but the phase increments between frames are preserved. iii) Synthesis: The inverse short-time Fourier transform is performed on each frame spectrum. Each frame is then overlap-added to return to the time domain.

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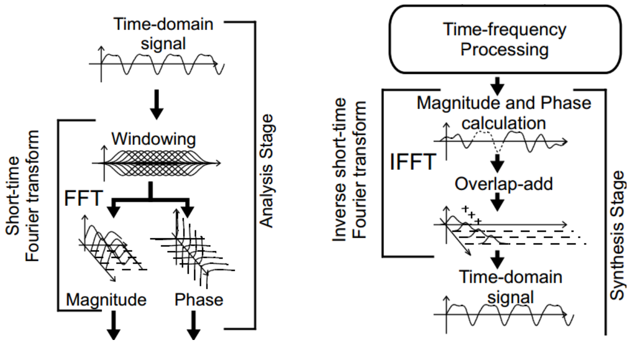

Figure 5. The flowchart of phase vocoder.

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