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Comparative Evaluation of an Ambulatory EEG Platform vs. Clinical Gold Standard

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Abstract— **Electroencephalography (EEG) testing in clinical labs makes use of large amplifiers and complex software for data acquisition. While there are new ambulatory electroencephalogram (EEG) systems, few have been directly compared to a gold standard system. Here, an ultra-low power wireless EEG system designed by Imec is tested against the gold standard Neuroscan SynAmps2 EEG system, recording simultaneously from the same laboratory cap prepared with electrode gel. The data was analyzed using correlation analysis for both time domain and frequency domain data. The analysis indicated a high Pearson's correlation coefficient (mean=0.957, median=0.985) with high confidence (mean P=0.002) for 10-second sets of data transformed to the frequency domain. The time domain results had acceptable Pearson's coefficient (mean=0.580, median =0.706) with high confidence (mean P =0.008).**

I. Introduction

Monitoring EEG in ambulatory environment is becoming more important not only in clinical domains but as an extra parameter for various life-style, brain computer interface (BCI) and entertainment applications. In order to address a wide variety of clinical applications, it is important to have a system that is miniaturized, wearable, wireless and provides flexibility and comfort to the user.

The Imec group [1-3] has created an 8-channel ultra-low-power wireless EEG system that acquires EEG data and wirelessly transmits to a USB-connected receiver. In order to analyze data quality, it was determined that the ideal method would be to connect a single EEG cap to both the wireless system and to the gold standard NeuroScan SynAmps system, which is used extensively in clinical research applications. NeuroScan lists many articles in applied neuroscience, in research involving MRI/EEG recordings, and in sensory neuroscience in where NeuroScan equipment is used [4].

There is a lack of data available on the quality of ambulatory EEG systems compared to clinical standard systems. NeuroSky, a manufacturer of single-lead dry EEG systems, published their own white paper [5] in which they gave correlation coefficients for Fourier-transformed EEG signals from their dry sensor EEG system to the wet electrode Biopac system, which is used in medical and research applications. Signals were simultaneously recorded from side-by-side electrodes. They provided results for a single subject tested with approximately 30 seconds of data, with no correlation coefficient above 0.858 recorded in the frequency domain. Matthews et al[6] of QUASAR produced a study comparing novel hybrid EEG electrodes to conventional wet electrodes in side-by-side testing which produced high levels of correlation (>99% for seated subjects in the frequency domain).

Neither of these studies, however, tested two systems using the same headgear, which eliminates any differences resulting from discrepancies in electrode positioning, material, and stimulus effects. In this study, all testing was done simultaneously with the wireless EEG system and a gold standard NeuroScan SynAmps system using a standard 64-channel EEG cap.

II. Methods

A. Subjects

Nine healthy control subjects were tested in the EEG laboratory at the Centre for Addiction and Mental Health (CAMH) in Toronto, Canada. All subjects passed a screening process that ensured their eligibility as healthy controls. This included collecting their basic medical history. We excluded subjects with a psychiatric history, as well as any mental health history of first-degree relatives. All subjects gave their written informed consent and the protocol was approved by the Centre for Addiction and Mental Health in accordance with the Declaration of Helsinki.

B. Equipment

The 8-channel wireless EEG system developed by Imec is shown in the figure 1a below, at top left. The system builds on an EEG Application-Specific Integrated Circuit (ASIC)

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that achieves high-performance at low power consumption [2]. The system has a low-noise (62 nV/√Hz), high common mode rejection ration (120dB). It has been optimized for low power consumption and consumes between 3.3mW and 14mW depending on the mode of operation [3]. Its packaging included connectors for EEG DIN cables. In order to evaluate the signal quality, it was compared to NeuroScan's SynAmps amplifier system, which can be connected to a 64-channel EEG cap. The SynAmps connector is shown in the figure 1b below, at top right. A 64-channel Quik-Cap from NeuroScan was used, with only 8 channels plus reference and ground being prepared with EEG gel to minimize their impedances. The specific channels used are shown in figure 2. The Quik-Cap is shown in the figure 1c below, at bottom right. A pin-out board was created so that the 80-pin connector on the Quik-Cap could be connected both to the SynAmps system and to the Imec EEG ASIC. The connector board is shown in the figure 1d below, at bottom left.

Figure 1: **Equipment setup** (clockwise from top left) a) Imec 8-channel EEG ASIC; b) NeuroScan SynAmps connection; c) NeuroScan Quik-Cap 64-channel EEG cap; d) Custom-made 80-pin connection board.

C. Test Protocol

The subjects completed baseline EEG readings, including 10 minutes of resting EEG (eyes closed), and 5 minutes of watching an emotionally neutral video clip (eyes open) from Disney's "Silly Symphonies" without audio. These were completed in a counterbalanced order.

After the baseline readings, the subjects completed N-back working memory tests (N=0, 1, 2) in random order and counterbalanced. Each of these tests was 13-15 minutes long.

In order to obtain meaningful correlation, simultaneous testing was required. Since only 8 channels could be used by both systems, 4 pairs of parallel electrodes were chosen for testing. They are shown in the figure below. Frontal polar (FP1, FP2), anterior frontal (AF3, AF4), frontal (F5, F6) and central (C3, C4) electrodes were used. Each electrode was prepared with electrode gel as electrode impedances were lowered to < 5kΩ. Channels were referenced to an electrode placed posterior to the CZ electrode.

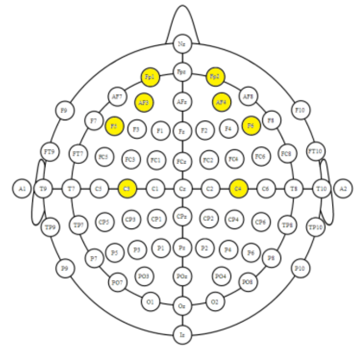

Figure 2: Electrodes from 10-20 system used for testing.

III. Analysis

Acquired data was post-processed using MATLAB. The NeuroScan acquired signals were sampled at 1000 Hz, and the Imec acquired signals were sampled at 1024 Hz. To correct this, a native resampling function in MATLAB was used to down-sample the Imec data to 1000 Hz to match the NeuroScan sampling rate. Next, the data was aligned using an original function that checked the correlation between the data sets by moving the first 5 seconds of the Imec data by milliseconds against the NeuroScan data and finding the correct offset. After matching the offset, the beginning and end of each set was trimmed to make them each even multiples of 5 seconds and to remove data that may have been affected by the down-sampling. After aligning the data and dropping the front and back, there were a total of over 7.5 hours of data used.

The data was then transformed from time domain to the frequency domain using overlapping 2-second windows using MATLAB's FFT function at 0.25 Hz resolution. The overlap was 1 second, so the time domain data was converted for segments from 0-2 s, 1-3 s, 2-4 s, etc. for each test. To match clinical EEG use, the frequency domain data from 1-50 Hz was used for correlation, with 201 total points from the 0.25Hz resolution (i.e. 1.00 Hz, 1.25 Hz, 1.50 Hz, etc). This was also split into δ (1-3.5Hz), θ (4-7Hz), α (8-12Hz), β (12.5-28Hz) and γ (30-50Hz) bands. The same analysis was also done for 10-second time windows with 5-second overlaps (0-10 s, 5-15 s, etc). A correlation analysis returned the Pearson's correlation coefficient (R) and confidence value (P) for each set, and then means and medians of different subsets were isolated. The results are presented below.

IV. Results

TABLE I
PEARSON'S CORRELATION COEFFICIENTS
(2-SECOND WINDOWS)[a]

Band (# of Points)	**Pearson's Coefficient (R)**			
	Mean	***Median***	***Variance***	$R^2>0.5$
All (201)	0.9303	0.9757	0.00001	94.68%
Delta (11)	0.8110	0.9528	0.00016	80.62%
Theta (13)	0.8383	0.9552	0.00011	83.76%
Alpha (17)	0.8357	0.9612	0.00021	82.87%
Beta (63)	0.8325	0.9414	0.00024	82.30%
Gamma (83)	0.7839	0.8768	0.00011	78.07%
Time (2001)	0.5520	0.6688	0.00015	41.73%

a. 215,880 total sets for correlation from 7.5 hrs of testing

TABLE Ib
CONFIDENCE VALUES OF CORRELATION

Band (# of Points)	**Confidence (P-value)**		
	Mean	***Median***	***Variance***
All (201)	0.00072	<1E-50	3.5E-7
Delta (11)	0.0560	4.4E-5	5.6E-5
Theta (13)	0.0453	3.7E-7	2.1E-5
Alpha (17)	0.0497	8.6E-10	4.6E-5
Beta (63)	0.0211	1.9E-30	1.9E-5
Gamma (83)	0.0263	1.7E-26	2.4E-5
Time (2001)	0.0171	<1E-50	7.6E-7

TABLE II
PEARSON'S CORRELATION COEFFICIENTS
(10-SECOND WINDOWS)[b]

Band (# of Points)	**Pearson's Coefficient ®**			
	Mean	***Median***	***Variance***	$R^2>0.5$
All (201)	0.9570	0.9848	0.00001	97.83%
Delta (11)	0.9070	0.9647	0.00009	93.95%
Theta (13)	0.9124	0.9834	0.00009	92.84%
Alpha (17)	0.9064	0.9797	0.00018	91.15%
Beta (63)	0.8922	0.9637	0.00014	90.10%
Gamma (83)	0.8467	0.9215	0.00006	86.96%
Time (2001)	0.5804	0.7063	0.00008	45.27%

b. 42,888 total sets for correlation from 7.5 hrs of testing

TABLE IIb
CONFIDENCE VALUES OF CORRELATION

Band (# of Points)	**Confidence (P-value)**		
	Mean	***Median***	***Variance***
All (201)	0.0018	<1E-50	3.8E-7
Delta (11)	0.0148	1.6E-6	3.1E-6
Theta (13)	0.0197	1.7E-9	4.7E-6
Alpha (17)	0.0205	8.2E-12	1.3E-5
Beta (63)	0.0110	7.5E-36	7.3E-6
Gamma (83)	0.0121	3.7E-34	4.7E-6
Time (2001)	0.0084	<1E-50	3.0E-6

Over the range of clinical EEG bands, very high correlation was seen between the two systems. The correlation for each of the Delta, Theta, Alpha, Beta and Gamma bands was very high as well, with significant p-values. The correlation values improved with larger windows, suggesting that small errors were not as significant depending on the size of window used. It was noted that the results of all bands together are not an average of the individual bands. This is likely due to the algorithm used by the correlation function in MATLAB, which would be more forgiving to a 201-point data set.

The time domain signal was not as well correlated. This may be due in part to electrical noise, as the NeuroScan system used AC power while the Imec system ran on a DC battery. The NeuroScan system also excelled at eliminating offset or drift, but these issues were largely removed by conversion to the frequency domain.

V. Conclusion

While the Imec system was susceptible to some noise in the time domain, its frequency domain results compared favourably to the gold standard NeuroScan system. In particular, for the 1-50 Hz range, if nearly 95% of values had a coefficient of determination (R^2) above 0.5, then in a 60-second sample where moving 2-second windows were compared, approximately 57 seconds of the data are well correlated. For clinical EEG that is used for evaluation of emotional state, this would provide more than sufficient information. By reanalyzing the data with 10-second windows, the results were improved across all bands. It is possible that changing the time window further would improve results, as small errors and noise would be reduced further with longer windows. Depending on the application of the system, a large enough window would provide near-perfect results. In the future, this testing will be used to validate a full wireless MBAN system for ambulatory monitoring of subjects with mental illness. Results indicate that this system has comparable fidelity to clinical gold standard system.

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REFERENCES

[1] B. Büsze et al, "Ultra low power programmable biomedical SoC for on-body ECG and EEG processing", in *2010 IEEE Asian Solid-State Circuits Conference*, Beijing, CN, Nov. 8-10, 2010, pp. 341–344.

[2] R.F. Yazicioglu, P. Merken, R. Puers, C. Van Hoof, "A 200 μW Eight-Channel EEG Acquisition ASIC for Ambulatory EEG Systems", in *IEEE Journal of Solid-State Circuits.* Vol. 43, No. 12, pp. 3025-3038.

[3] S. Patki, B. Grundlhener, T. Nakada, J. Penders, "Low-power EEG headset for BCT applications", 14th International Conference, HCI International 2011, Orlando, FL, USA, July 9-14, 2011, Proceedings, Part II, pp. 481-490

[4] NeuroScan. "Peer-Reviewed Articles by Solution." Available: http://www.neuroscan.com/articles.cfm Accessed: November, 2012.

[5] NeuroSky. "Brain Wave Signal (EEG) of NeuroSky, Inc." NeuroSky, Inc. December 15, 2009. Available: http://www.neurosky.com/AcademicPapers.aspx

[6] R. Matthews et al. "Novel Hybrid Bioelectrodes for Ambulatory Zero-Prep EEG Measurements Using Multi-channel Wireless EEG System", in *Foundations of Augmented Cognition: Lecture Notes in Computer Science*, vol. 4565, Springer Berlin Heidelberg, 2007, pp. 137-146.