NeuroRegulation

Comparing DC Offset and Impedance Readings in the Assessment of Electrode Connection Quality

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Abstract

Electroencephalograph (EEG) electrode impedance measurements of 5,000 ohms or less are required by common standards of practice to minimize artifacts due to electro-magnetic interference (EMI). Some amplifiers geared toward the neurofeedback market do not include on-board impedance monitoring, but provide direct current (DC) offset measurements. To examine if DC offset is a reliable measure of connection quality, measurements of DC offset and impedance, each independently taken by students in a university graduate level course in neurofeedback over a one-year period were analyzed retrospectively. DC offset was not found to have predictive value of a standard impedance level. Additionally, 19 channel EEGs collected within manufacturer recommended parameters of DC offset using a high-impedance amplifier were analyzed to assess the level of EMI pollution of quantitative EEG (QEEG) data. Visible peaks of EMI in the spectra in at least one channel in each of these recordings were identified. A sample of EMI pollution of QEEG results is presented. Together, these findings suggest that DC offset may not be a reliable measure of electrode connection quality.

Keywords: EEG, electrode, interference, impedance, DC offset, QEEG

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Introduction

Many factors are inherent in the quality of an electroencephalograph (EEG) recording, among which are artifact reduction, electrode stability, and the highest possible signal-to-noise ratio. Electro-magnetic interference (EMI) can potentially invade the EEG recording. The 50 Hz or 60 Hz signature of the building's electrical mains is a primary source of EMI. Other sources of EMI, such as radio, may be present in the recording environment. Since the typical neurofeedback provider may not be operating in a shielded room, these sources of EMI are often present, as indicated by artifacts in the traces and characteristic peaks in the spectra. Traditionally, the quality of the electrode connection has been seen as instrumental to ameliorating these factors as achieved by attaining low impedance between the leads. The importance of low impedance for achieving electrode connection quality is well established and continues to be recommended in EEG textbooks (Tatum, 2014; Tyner, Knott, & Mayer Jr., 1983). Impedance measurement below 5,000 ohms remains the adopted standard for EEG recordings (American Association of Sleep Technologists, 2012; American Clinical Neurophysiology Society, 2008).

Modern high-impedance amplifiers reduce the effect of EMI considerably to the extent that some have suggested that the 5,000-ohm impedance standard is no longer relevant or safe if it requires skin abrasion (Ferree, 2001). Historically, some amplifiers have been manufacturerd without on-board impedance measurement and instead include software-assessable direct current (DC) offset measures as an indication of connection quality.

Kappenman and Luck (2010) reported that high electrode impedance may decrease the signal-to-noise ratio and statistical power in event-related potentials (ERP) recordings, even with equipment designed to tolerate high impedance levels. Though they found that these effects may be ameliorated with a cool and dry recording environment, they recommended that high impedance EEG equipment manufacturers accommodate the need for skin abrasion and impedance monitoring for experiments that require high statistical power.

Whereas impedance is a measure of the conductance of electricity through the skin between a pair of leads, DC offset is a by-product of the DC potentials generated at the junction of the skin and electrolyte solution under the electrodes resulting in a voltage at the amplifier inputs (Kamp, Pfurtscheller, Edlinger, & Lopes da Silva, 2005). Theoretically, it is assumed that the lower the offset, the better the connection.

This study examines the relationship between DC offset and impedance as measurements of electrode connection quality. The hypothesis under investigation in this study is that if DC offset is a reliable measure of electrode connection quality, it will correlate with impedance.

The significance of this study is not merely academic but is intended to be applied to the clinical practice of neurofeedback. Neurofeedback practitioners, as a whole, utilize equipment of various levels of quality, in environments with various levels of EMI, and with various levels of skill in assessing the quality of the EEG signal they are training. Furthermore, a summary of case studies will be presented that indicates the distortion of quantitative EEG (QEEG) results by EMI using high impedance equipment. If, in the clinical practice of neurofeedback practitioners, EMI can adversely affect the processing of the EEG, having a reliable way to assure electrode connection quality is important.

Methods

Measurements of DC offset and impedance, each independently taken by students in a university graduate level course in neurofeedback over a 1-year period using standardized data collection procedures, were analyzed retrospectively. The retrospective study of DC offset and impedance was approved by the Institutional Review Board of the University of Texas at San Antonio. For the retrospective study of EEG recordings, the subjects were protected and the data was collected in accordance with the Declaration of Helsinki.

Procedures

For the DC offset and impedance study, the following procedures were followed. Initial site preparation was done by cleaning with a 91% isopropyl alcohol-soaked cotton ball, scrubbing with an alcohol-soaked gauze impregnated with an abrasive (PDI Electrode Prep pads), and additional scrubbing with an abrasive skin prepping gel (Nuprep). A single channel set of electrodes was then placed on the scalp using conductive paste (Ten20). Central placements according to standard 10–20 EEG placements were used for the active electrode with bilateral mastoid placements for the reference and ground electrodes. Ag/AgCl snap electrodes were used, which were inspected to insure that the pellet coating was not worn, and each set of pellets were used no more than three times. DC offset was measured using high-impedance amplifiers and accompanying software. After DC offset was measured, impedance was measured between active and reference, active and ground, and reference and ground electrodes. Only the active-reference impedance values were used in the comparative analysis, since the DC offset measurements recording in the software reflect the active-reference connection only. The data consist of 181 points measuring two variables, impedance (1000’s ohms) and DC offset (+/- 1000’s microvolts).

To evaluate the effects of EMI on EEG recordings, 27 19-channel recordings made in a single private practice setting over a period of 8 months were analyzed. Vendor-recommended preparation procedures were used to insure that DC offset readings via the accompanying software read between +/- 25,000 uV for all channels.

Equipment

The following equipment was used for the DC offset and impedance study. Each measurement utilized one of four amplifiers, consisting of three NeXus-4 (Mind Media, The Netherlands) and one NeXus-10 amplifiers (input impedance > 10 Tohm) with accompanying BioTrace software. Since the EEG systems utilized LEMO or ODU brand connectors (push-pull circular shielded connectors with six pins) an adapter was used to connect to a 1089NP Checktrode impedance meter with standard DIN connectors. The recordings analyzed for the EMI case study were all made using one NeXus-32 high-impedance amplifier (input impedance > 10 Tohm) with accompanying BioTrace software and manufacturer-supplied caps.

Analysis

For the retrospective DC offset and impedance study, two analyses were used. The first analysis involved simply plotting the data and computing the sample correlation. Since there were only two variables, plots provide good evidence of the type of relationship between impedance and DC offset, and a correlation close to 1 would indicate a strong linear relationship. The second analysis was a more detailed evaluation that computes confusion tables between DC offset above and below different thresholds and impedance above and below 5,000 ohms. Confusion tables are 2 x 2 tables that calculate the number of true positive, true negative, false positive, and false negative samples. Various statistical performance measures and the receiver operating characteristic (ROC) curve were calculated to show how well DC offset predicted a good connection. The statistical performance measures used were accuracy, precision, and sensitivity. Accuracy was calculated as the number of correct classifications divided by the total (true positives + true negatives divided by the total). Precision was calculated as the positive predicted value (true positives divided by true positives + false positives). Sensitivity was calculated as the true positive rate or hit rate (true positives divided by true positives + false negatives). All performance measures range from 0 to 1. For DC Offset to be a reliable predictor of impedance, it was hypothesized that there should be high levels of accuracy, precision, and sensitivity (close to 1). Also, to reflect high predictability of DC offset to impedance, the area under the ROC curve should be close to 1.

Using spectral analysis, one channel was selected from each of the 27 19-channel recordings that reflected the highest power at 60 Hz. For comparison purposes, these single-channel spectra were combined into one FFT spectra graph (Figure 5). The QEEG statistics were then examined for the recordings to determine if the suspected peaks corresponded with a distortion of the data and *Z*-score statistics.

Results

The results of the study are presented here in three parts. Two analyses were conducted for the DC offset and impedance measurements: (1) plots and correlation, and (2) confusion matrices and receiver operating characteristic curve. The third section presents the results of a case study of EMI in a group of 19-channel EEG recordings.

Analysis 1 of DC Offset and Impedance Measurements: Plots and Correlation

The Pearson Sample Correlation between impedance and DC offset was computed to be 0.092. The plots of impedance vs. DC offset (Figures 1, 2, and 3) and a correlation of 0.092 suggest there is not a linear relationship between impedance and DC offset. Figure 1 reflects the range of all samples collected, Figure 2 plots impedance readings < 15K ohms, and Figure 3 includes plots of DC offset readings < 50K uV.

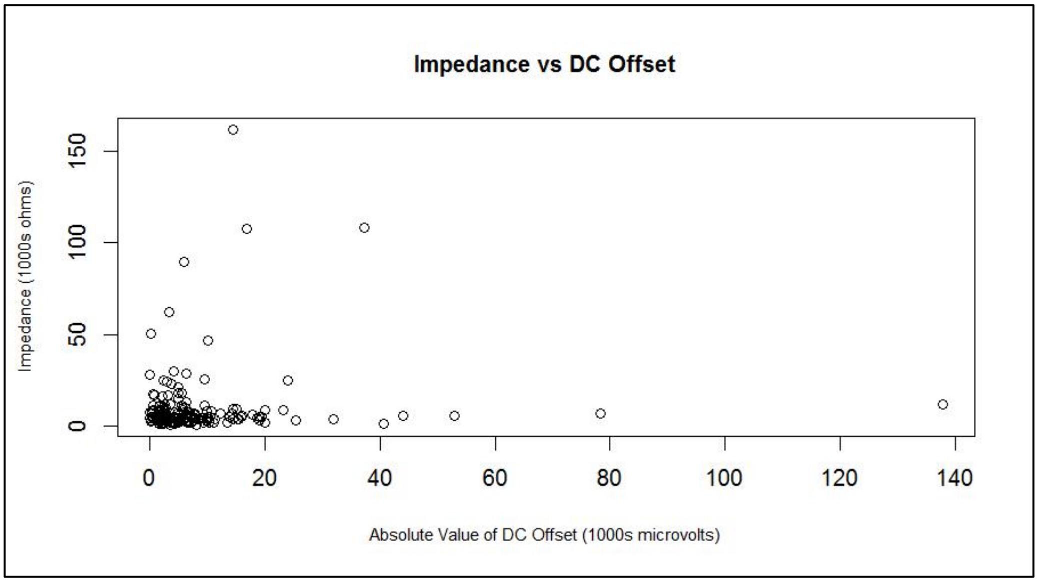

Figure 1. Impedance vs. DC offset reflecting the range of all samples collected.

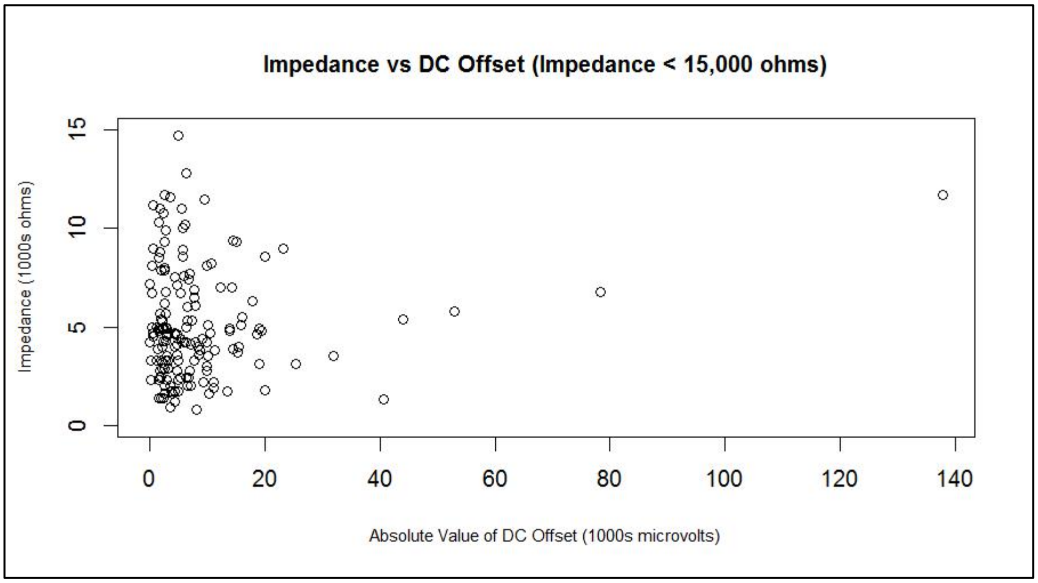

Figure 2. Impedance vs. DC offset showing plots of impedance readings < 15K ohms.

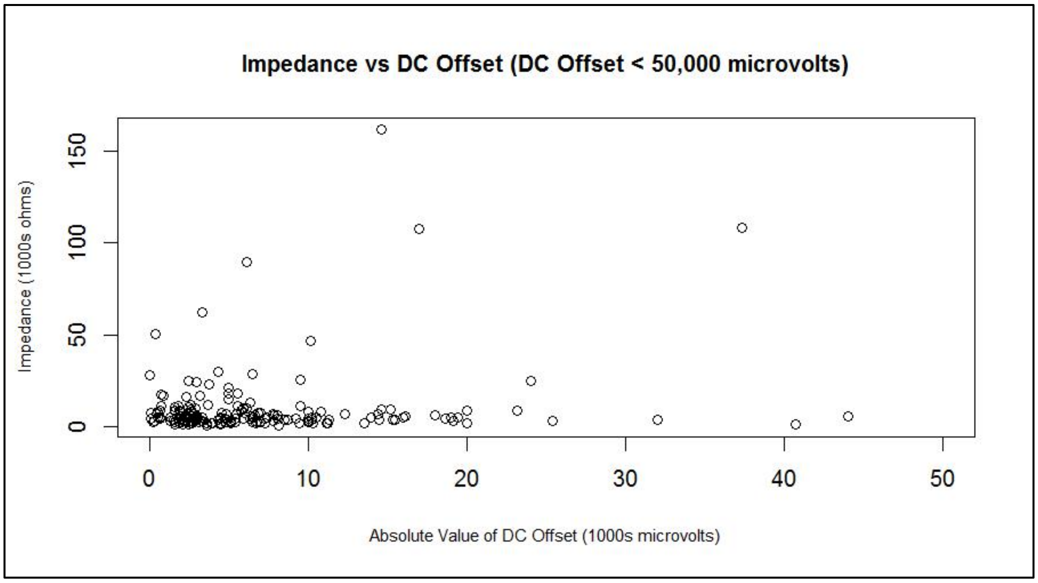

Figure 3. Impedance vs. DC offset showing plots of DC offset readings < 50K uV.

Analysis 2 of DC Offset and Impedance Measurements: Confusion Matrices and Receiver Operating Characteristic Curve

Using impedance less than or equal to 5,000 ohms as a good connection, and greater than 5,000 ohms as a bad connection, four confusion matrices are shown below for good levels of DC offset at less than or equal to 5,000; 15,000; 25,000; and 35,000 microvolts (Table 1). The analysis used the absolute value of the DC offset measures, referred to as |DC Offset|.

The confusion matrices analysis shows accuracy and precision all below 60% for four different thresholds of DC offset, which indicates poor predictability of impedance above and below 5,000 ohms. The low precision and accuracy levels are a result of the relatively high number of false positives (refer to the upper right hand corner of each confusion table). While sensitivity is high (above 90%) for |DC Offset| thresholds above 15,000, this comes with low precision and accuracy.

Table 1
Confusion Matrices

Confusion Matrix 1	Impedance ≤ 5,000 (ohms)	Impedance > 5,000 (ohms)
|DC Offset| ≤ 5,000 (microvolts)	54	39
|DC Offset| > 5,000 (microvolts)	45	43
Accuracy	Precision	Sensitivity
0.536	0.581	0.545

Confusion Matrix 2	Impedance ≤ 5,000 (ohms)	Impedance > 5,000 (ohms)
|DC Offset| ≤ 15,000 (microvolts)	89	69
|DC Offset| > 15,000 (microvolts)	10	13
Accuracy	Precision	Sensitivity
0.564	0.563	0.899

Confusion Matrix 3	Impedance ≤ 5,000 (ohms)	Impedance > 5,000 (ohms)
|DC Offset| ≤ 25,000 (microvolts)	96	77
|DC Offset| > 25,000 (microvolts)	3	5
Accuracy	Precision	Sensitivity
0.558	0.555	0.970

Confusion Matrix 4	Impedance ≤ 5,000 (ohms)	Impedance > 5,000 (ohms)
|DC Offset| ≤ 35,000 (microvolts)	98	77
|DC Offset| > 35,000 (microvolts)	1	5
Accuracy	Precision	Sensitivity
0.569	0.560	0.990

Note: |DC Offset| refers to the absolute value of DC Offset.

A more robust measure of how well DC offset predicts impedance is to calculate the ROC curve, as shown below (Figure 4). The ROC curve shows the true positive rate vs. false positive rate at 1,000 equally spaced thresholds of DC offset from 0 to 140,000 microvolts. Here once again, a good connection represents impedance less than or equal to 5,000 ohms. To reflect high predictability of DC offset to impedance, the area under the ROC curve should be close to 1 (the ideal test line) on the true positive scale rather than close to the random guess line. The results of the ROC analysis shows area under the ROC curve is approximately 0.50. This suggests that DC offset is no better at predicting the quality of a connection than randomly guessing.

Case Study of EMI in 19-Channel EEG Recordings

For the retrospective case study, the one-channel spectral graphs selected from all 27 recordings were combined to enable visual examination (see Figure 5). Based on this examination, four suspected EMI-related peaks were identified. A tabulation of the percent of samples with visible peaks in four suspected frequencies ranges was done to determine how many recordings displayed a visible peak against the background (see Table 2).

All of the recordings had at least one channel that displayed a visible peak at 60 Hz; at least half with visible peaks in the other three suspected frequencies. The sites in question appeared randomly located; they were not confined to specific sites. As seen in the combined spectra, the power of the peaks suggests that they are of artifactual origin, i.e., they do not follow the 1/frequency characteristic and appear higher than would be expected from cortical sources. Furthermore, in visual inspection of the recordings, the suspected peaks appear to rise and fall together with the 60 Hz peak, suggesting they may share a common EMI source or a common sensitivity to EMI at these respective frequencies.

Table 2
Percent of samples with visible peaks in four suspected frequencies ranges.

Peaks	19-21hz	31-33hz	47-49hz	59-61hz
Visible	50%	88.5%	57.7%	100%

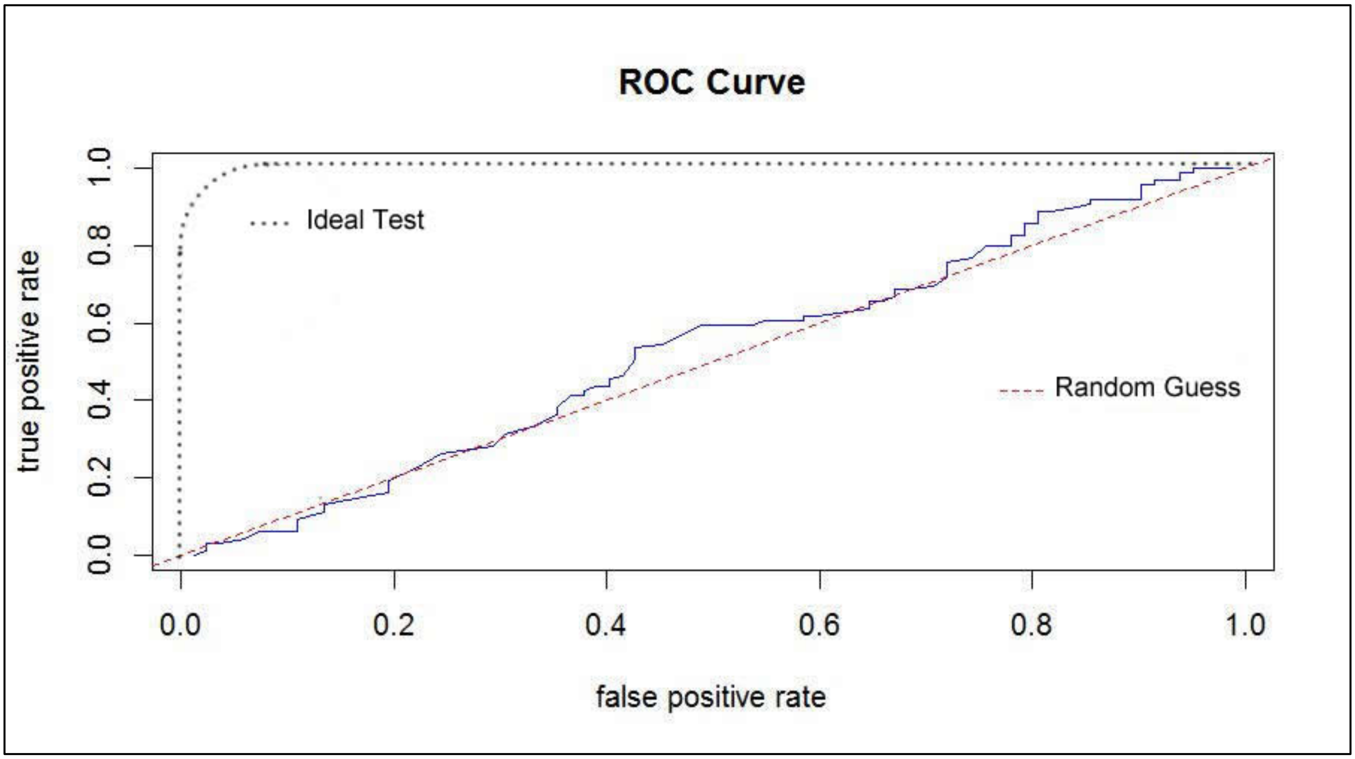

Figure 4. Receiver Operating Characteristic (ROC) curve showing true positive rate vs. false positive rate.

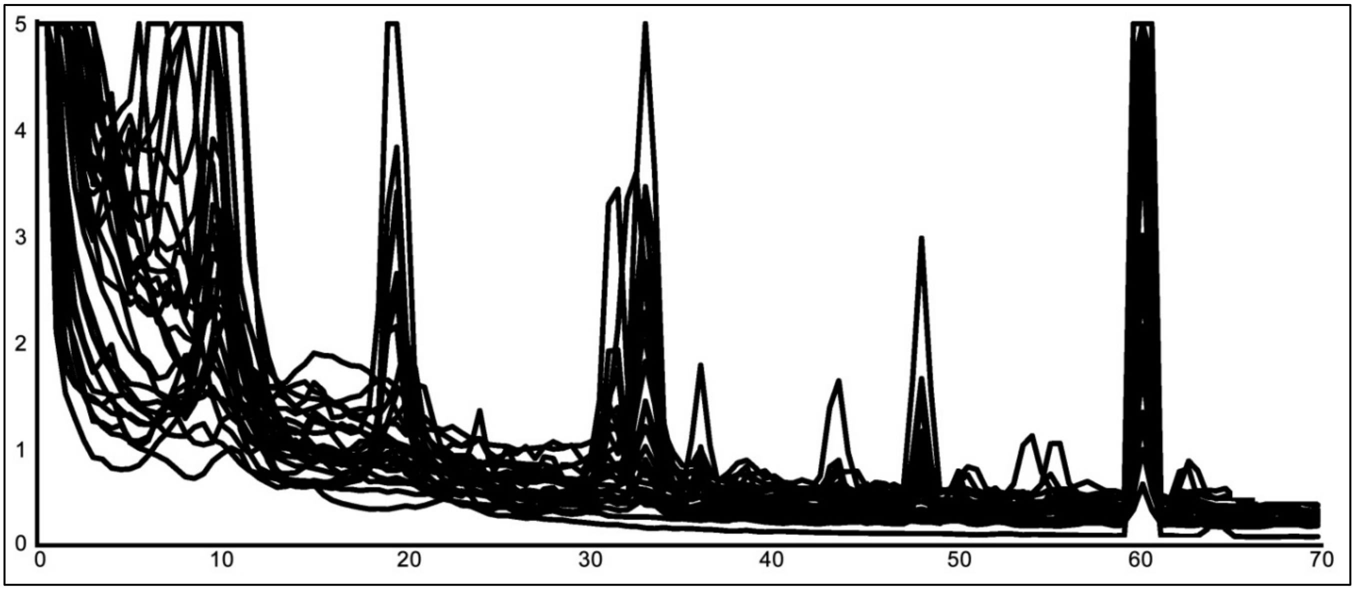

Figure 5. Combined FFT spectra from selected channels from 27 recordings, y-axis-range 5.00 uV peak-to-peak, x-axis-range 0–70 Hz, 512 samples/s, FFT epoch 2 s, FFT points 1024 samples, BIN size 0.50 Hz, Hanning windowing, overlap step 250 ms. All channels in all recordings had DC offset readings of +/- 25K uV.

Upon examination of QEEG *Z*-scores (1–30 Hz), it was found that the 19–21 Hz peak was represented in the data. Figure 6 is an example of the *Z*-score absolute power spectrum of a 19-channel recording with significant EMI artifact, showing a 19–21 Hz peak. For QEEG databases capable to processing activity higher than 30 Hz, it is assumed that the 31–33 Hz peak would also distort the *Z*-score data.

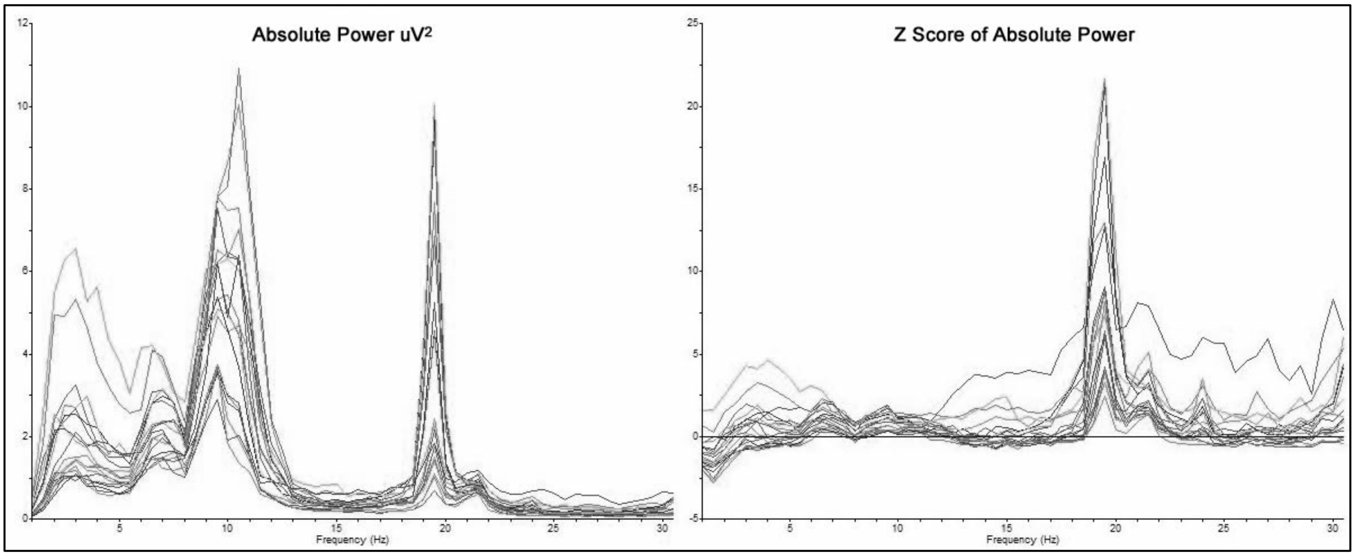

Figure 6. Example of the absolute power (left) and *Z*-score absolute power (right) spectra of a 19-channel recording with significant EMI artifact, showing a ~19 Hz peak in multiple channels. All channels had DC offset readings of +/- 25K uV.

Conclusion

Statistical analysis of common DC offset and impedance measurements suggests that DC offset may not be a reliable measure of electrode connection quality as compared to impedance. A linear relationship between the two measures was not found. A significant number of false positives demonstrated that DC offset may be a poor reflection of connection quality. Plotting the ROC curve showed that DC offset is no better at predicting the quality of a connection than randomly guessing in this study. Furthermore, analysis of case study recordings was presented which suggested the possibility that poor connection quality may result in the distortion of QEEG results.

The analysis of the case study data was included to illustrate the possibility of EMI artifact encroachment into the QEEG data at frequencies generally associated with cortical activity (up to approximately 40 Hz or more). Since many neurofeedback systems do not have the capability of measuring 60 Hz activity, such encroachment would be difficult to detect and might present as localized over-arousal or some other mystifying finding. It also follows that the ability to measure EMI artifact at 60 Hz (or 50 Hz) is one possible way to assess the electrode connection quality.

Impedance remains the conventional means of testing the quality of electrode connection. The current impedance requirements by the American Clinical Neurophysiology Society and the American Association of Sleep Technologists appear to be validated by the findings presented in this paper.

It is assumed that the software-based DC offset measurements available in the systems used in this study measure the effects of voltage difference between the active and reference electrodes only. This allows for no assessment of the quality of the ground electrode connection. Some impedance measurements in the study data showed a poor ground connection, which wasn't accessible via the DC offset measurements. This highlights an additional problem of using DC offset measures as a method of determining electrode connection quality; without a sufficient ground connection, the EEG signal can become unstable. To insure a good quality electrode connection, it is important to measure impedance between active, reference, and ground leads.

Given the technological limitations of the methods used in this study, further research into the relationship between DC offset and impedance, as well as the susceptibility of EMI artifact in the often-uncontrolled environments where neurofeedback is practiced, is warranted. Such future research would be strengthened with the inclusion of a representative variety of equipment manufacturers with duplication in the number of devices. Additionally, the independent analysis of commonly used equipment in a laboratory setting would be advantageous. Beyond the research arena, it is recommended that certification of neurofeedback practitioners include the evaluation of skills needed to adequately assess the quality of electrode connection, including the importance of monitoring impedance.

Another limitation of the study was the subjective nature of the assessment in the QEEG case study. The spectra of the 27 recordings were inspected in order to identify the channel with the highest level of 60 Hz interference. These channels were then combined into a single spectral graph where peaks were identified by visual examination. A more statistically robust method of selecting the relevant channels and finding significant variations would strengthen the conclusions regarding EMI interference.

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