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Variability in AC amplifier distortions: Estimation and correction

C. A. JOYCE,[a] I. F. GORODNITSKY,[b] W. A. TEDER-SÄLEJÄRVI,[c] J. W. KING,[d] AND M. KUTAS[b,c]

[a]Department of Computer Science, University of California, San Diego, California, USA
[b]Department of Cognitive Science, University of California, San Diego, California, USA
[c]Department of Neurosciences, University of California, San Diego, California, USA
[d]Department of Psychology, University of Missouri, Columbia, Missouri, USA

Abstract

AC amplifiers can introduce significant distortions into the low frequency and DC components of recorded electrophysiological data such as event-related potentials (ERPs). Methods for correcting such distortions (i.e., estimating the waveform of the original data) *after* the data have been amplified and recorded rely on an accurate estimate of the amplifier's time constant (TC). We show that the filter characteristics of AC amplifiers in at least some commercially available ERP recording instruments may vary considerably across individual channels, even when each houses an identical AC amplifier circuit. Clearly, distortion correction methods must take this variability into account. We propose an empirical means of estimating the correct TC value. This approach yields more accurate correction than those based on TCs calculated analytically.

Descriptors: Time constant, AC-amplifier fluctuations, DC recovery

Many ERP laboratories use AC rather than DC amplifiers because of their stability and ease of calibration. An AC-coupling circuit acts as an analog filter that attenuates and phase shifts the input voltage as a function of an amplifier's time constant (TC; e.g., Elbert and Rockstroh, 1980; Gasser, Kneip, & Verleger, 1982). AC amplifiers affect predominately the low frequency—DC and near DC—components of the signal. This distortion must be corrected whenever a researcher wishes to analyze DC and near DC components or to compare two data sets recorded with different time constants.

The work reported herein was instigated by our investigations using electrooculograms (EOGs) to monitor eye movements (especially saccades), as these are characterized by slow wave potentials and DC components lasting several seconds (e.g., fixations). In working with DC signals, we discovered that even small errors in the TC estimate are immediately evident and that using TCs computed from amplifier specifications supplied by manufacturers led to significant errors in tracking eye movements. Using calibrated trials, we were able to trace these errors to deviations in AC amplifier filter characteristics from the standard values expected based on the manufacturer specifications. Further investigation revealed that the amplifier filter characteristics can vary considerably across amplifier channels with (presumably) identical settings. This was observed initially using one instrument but was subsequently reproduced with three other EEG systems from various major manufacturers, which were maintained in independent, physically separate laboratories in different academic departments at the University of California, San Diego. Such variability in the actual filter characteristics of commercially available amplifiers can be the source of errors if analytical TCs are used to estimate undistorted waveforms. Variability in amplifier responses has relevance for studies beyond those involving measurement of DC signals. As demonstrated by Duncan-Johnson and Donchin (1979) and Rockstroh, Elbert, Canavan, Lutzenberger, and Birbaumer (1989), both the amplitude and peak latency of some ERP components can be affected by the amplifier TC. To the extent that the TCs of channels within the same recording system differ and differentially affect the amplitudes or latencies of the ERP components across channels, inferences about distributional differences will be erroneous. More specifically, this may lead to the appearance of ghost peaks when, for example, current source density is estimated.

In this article, we report our findings from tests of amplifiers in four commercially available EEG systems and demonstrate the degree of amplifier response variations for these systems. We then offer some guidelines for estimating TC under these conditions, which we have found to work for our purposes. As this work represents a long chain of detective inductions, we think its telling

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Address reprint requests to: Marta Kutas, University of California, San Diego, Department of Cognitive Science, 9500 Gilman Dr., San Diego, CA 92093-0515, USA. E-mail: mkutas@ucsd.edu. Address technical questions to Irina Gorodnitsky (igorodni@ucsd.edu).

can save significant time and frustration for others using AC amplifiers to record data with DC and near DC components.

Variability of TC in Amplifier Circuits

Motivated to understand why the textbook approach we used to correct for the amplifier distortions did not yield the desired results, we measured the actual TC for each channel of the system whose output is depicted in Figure 1. The system under investigation was a bank of 32 Nicolet amplifiers, each made of a simple single-stage RC circuit. The standard definition of TC is the time needed to charge a capacitor to 63.2% of its capacity in a given circuit (Horowitz & Hill, 1980). Equivalently, TC is the time it takes for a capacitor to discharge to 36.8% of its capacitance. Thus, to measure TC directly, we produced square pulses of sufficient duration (~30 s) as input to our system and measured the time that it took the output to fall to 37% of its initial value. We used an interpulse interval of 30 s, allowing the amplifier system to recover completely between pulses. This was necessary in order to eliminate the effect of polarization in the amplifier circuit due to positive square pulses, thereby ensuring that any variations in amplifier response to the four consecutive 30-s pulses were due to the electronic circuitry alone. The TC values derived from four identical square wave pulses in each of the 16 channels of the Nicolet amplifier system are presented in the first four columns of Table 1. The filter and the sampling rate settings used were the same as those listed for Figure 1, with the low frequency cutoff, referred to as the LFF setting, set to 0.016 Hz. Even though the amplifiers were allowed to recover completely between pulses, there is considerable variability among the TC estimates across the four pulses in each channel. As can be seen in the last column of Table 1, the difference between the smallest and the largest mean TC estimate is 1.17 s, which is 18% of the average TC value collapsed across all channels and pulses. As discussed later in this report, TC can also be computed analytically for this simple

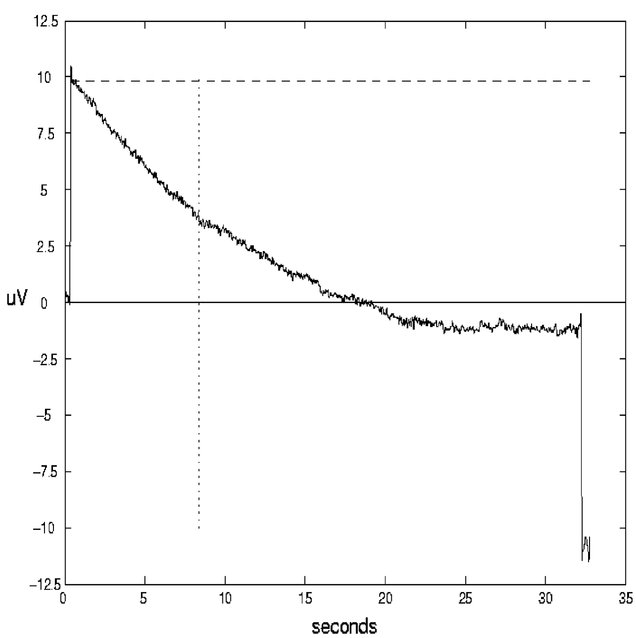

Figure 1. A sample 10-μV, ~30-s square pulse illustrating the recovery slope of the amplifier.

Table 1. *Time Constants[a] for Four ~30-s Square Pulses for 16 Channels of the Nicolet SM2000*

Channels	Pulse 1	Pulse 2	Pulse 3	Pulse 4	Mean
1	6.4220	7.7660	6.0100	6.7980	6.7490
2	6.1240	6.5720	5.9660	6.0780	6.1850
3	6.4840	7.5840	6.8580	6.7880	6.9285
4	7.0380	7.2420	7.7820	6.0960	7.0395
5	7.0840	6.8100	6.2280	6.8120	6.7335
6	7.2900	6.2820	6.6160	6.5740	6.6905
7	6.6060	7.1400	6.5180	6.3940	6.6645
8	6.5860	6.2020	6.9940	7.7140	6.8740
9	6.8560	6.5300	6.8840	6.7220	6.7480
10	5.7760	6.0460	5.9140	6.0480	5.9460
11	6.0020	6.3800	5.7400	6.0420	6.0410
12	5.9080	6.4120	5.5720	6.0060	5.9745
13	6.3600	6.5060	6.1880	5.9800	6.2585
14	6.6160	7.6220	5.4180	5.8300	6.3715
15	6.5840	5.4400	5.9220	5.5500	5.8740
16	7.0380	7.2160	5.7460	5.9160	6.4790

[a]TC was measured as the time to recover to 37% of the maximum amplitude of the square pulse signal.

single-stage circuit given the LFF = 0.016-Hz setting. The theoretical TC value for this circuit based on this analytic computation is 9.95 s, which is well outside the range of the actual TCs we measured. Clearly, such deviations of the actual channel TCs from the theoretical value and the variations in TCs among channels can cause a number of problems, including appearance of ghost peaks when examining slow potentials as well as problems associated with correcting for the amplifier distortions.

One practical problem raised by this example is how to empirically calibrate TCs. Calibration pulse generators built into commercially available EEG systems do not have an option for producing either long-duration pulses or long intervals between pulses. In our experience, the longest available standard pulses all have been under 1 s in duration. In the tests described above, we used an external calibration pulse generator to input much longer duration pulses. This custom modification is not readily available in most, if any, standard EEG amplification systems. In the next experiment, we examine measures taken from standard calibration pulses. We then discuss what can be done to estimate and correct for amplifier distortions given only short duration pulses.

In this second experiment, we test four EEG amplifier systems using standard calibration sequences with pulse durations of 100, 200, and 900 ms. These four commercial systems come from three different major manufacturers and are housed in three unrelated EEG laboratories in various academic departments at the University of California, San Diego. The instruments were independently installed and maintained by each individual laboratory. The systems range from 2 to 15 years old, but there seems to be no reliable correlation between the age of the amplifiers and the amount of the variability in the filter characteristics we measured. The systems and settings examined were as follows: (a) a Nicolet SM2000 AC amplifier, 10-μV amplitude pulses generated externally at a sampling rate of 250 Hz with a bandpass filter set from 0.016 to 100 Hz; (b) an SA Instrumentation Co. Isolated Bioelectric Amplifier System, Model SC-32/132BA, 20-μV amplitude pulses generated internally (10-μV pulses were not available on this system), at a sampling rate of 250 Hz and bandpass filtered from 0.01 to 100 Hz; and (c) two different Grass Instruments Model 12

Neurodata Acquisition Systems for EEG, 10-μV amplitude pulses generated externally at a sampling rate of 250 Hz and bandpass filtered from 0.01 to 100 Hz. All four systems housed single-stage circuit amplifiers.

The third column of Table 2 presents the range of TC estimates across the channels of each of the four EEG systems derived using linear regression (see Methods section for the TC estimation procedure we used). Note that for the Nicolet system, the empirical TCs estimated from short pulses (Table 2) are in precise agreement with the actual amplifier TCs measured in the long pulses (Table 1), validating the method used with short pulses. The TC estimates show that there is considerable variability in the recovery rates among channels housing identical amplifiers in the same EEG instrument. It is also important to note that these TC estimates reflect averaged filter characteristics based on hundreds of repeated pulses. The variability would be even greater if we were to estimate TC from only one or even a few arbitrary square wave pulses.

The last column of Table 2 presents the theoretical TC values for single-stage RC circuits, computed using the corresponding filter bandpass settings used in the experiment. TC for an RC circuit is computed analytically as

$$\mathrm{TC} = 1/(2\pi f[\mathrm{Hz}]), \quad (1)$$

where $f(\mathrm{Hz})$ is the low frequency cutoff setting (LFF) employed during data collection (Ruchkin, 1993). Whereas the analytic TC can be calculated using Equation 1 when the LFF used for recording differs from the one used by the manufacturer for the TC cited, it is clearly irrelevant if the amplifier response deviates significantly from the nominal value.

The discrepancy between the theoretical TCs and the empirically estimated TCs of each system is patent. For the Nicolet system we know that the empirical TCs that we estimated from short pulses reflect the true TC values. As one can observe from Table 2, the analytic TC = 9.95 s at 0.016 Hz LFF for this system is outside the range of the actual TCs in all the channels. The discrepancy between the theoretical TCs and the empirical TCs is even greater for the three other EEG systems listed in Table 2.

To check on our findings, we contacted the manufacturers of the last three EEG systems in Table 2 for which we could not generate long pulses to measure TCs directly. We requested amplifier specifications for these systems. For one of these systems, the manufacturer cited a TC value that was identical to the analytic value we obtained with Equation 1. This confirms that the amplifier circuit used in this system is, in fact, a standard RC circuit. The other company provided us with TC numbers for several LFF settings. Our understanding is that they obtained those numbers experimentally from a test circuit. The TC value provided to us for the LFF = 0.01 Hz setting we used in our experiments was 6 s; this was 4 s lower than the theoretical value and still outside the range of TC values that we measured. Providing a single TC number for a given LFF also clearly does not address the variability of amplifier responses across the different channels.

There are several possible explanations for the observed discrepancies in the TC values, which we discuss next. First we address the question of how we estimate TC from short pulses in this experiment and whether our estimation procedure may be responsible for the observed discrepancies. We estimate TCs shown in column three of Table 2 by fitting a line to the slope of the output amplitude falloff and projecting the line to the point at which the output has declined to 63% of its initial value. We use a long sequence of pulses and incorporate multiple stages of averaging and pulse sampling to obtain a stable slope estimate with this method (see Methods). It is commonly, but mistakenly, assumed that the amplifier output must follow an exponential rather than linear decline. In an exponential decline, the steepest falloff occurs in the first second after the pulse onset. In this case, a linear slope fitted to the steepest portion of the curve (which is all there is for short pulses), rather than to the whole interval including the flattened portion of the exponential decline, would underestimate the true TC value and this would explain the discrepancies between the numbers in the columns in Table 2. In the case of the amplifiers we tested, however, the output falloff is expected to be linear, as we explain next.

Single-stage RC circuits are simple to model and their behavior is easy to predict. The response of such a circuit at DC is always linear. The response curve gradually becomes exponential as LFF increases. Sample output curves for different LFFs can be observed, for example, in Figure 2 of Ruchkin (1993). The output curve only becomes measurably nonlinear around LFF = 0.1 Hz. Even so, a linear approximation works very well at this setting, which is a factor of 10 larger than the LFF = 0.01-Hz setting that we used to test three of the EEG systems. Even if these circuits were to operate outside their theoretical limits and exhibit a nonlinear response at LFF = 0.01 Hz, the deviation from the expected response would need to be unrealistically drastic to produce the response with a TC equal to the theoretical TC = 15.9 s. Specifically, the output curve would need to fall off to 50% of the original amplitude in the first 900 ms of the pulse and take 13.9 s to fall the remaining 16% to decline to 37% of its original value. This behavior would befit a system with LFF = 0.3 Hz, a factor of 30 greater than the LFF we used. Hence, from purely theoretical considerations, it is correct to estimate TC in this example using linear regression.

One also can perform a number of empirical tests to check the validity of the assumption that the response of these circuits is linear. In one such test, we compared the output slopes calculated from 100 ms, 200 ms, and 900 ms square pulses where they were available and found them to be virtually identical, indicating that falloff is linear at least across the first second of the response. Another possible test would be to examine DC signals in biological data to determine how well the empirical TC estimates approximate the actual filter response. For this purpose, we used horizontal and vertical eye movements, which generated DC signals up to 2 s in duration. Using such pattern templates for eye movements on calibrated trials, we determined that TCs estimated by fitting a linear slope to short calibration pulses yield appropriate corrections for amplifier distortions, whereas the TCs computed

Table 2. *Analytic and Empirical TC Values Computed for the Test Amplifiers*

	LFF (Hz)	HFF (Hz)	Empirical TC across channels (s)	Analytic TC (s)
Nicolet SM2000	0.016	100	5.67–8.51	9.95
SA Instruments SC-2/132BA	0.01	100	2.59–3.99	15.9
Grass Model 12 (a)	0.01	100	3.02–4.38	15.9
Grass Model 12 (b)	0.01	100	2.72–4.07	15.9

analytically yield grossly inaccurate estimates and corrections. To summarize, we find strong theoretical as well as some experimental support for approximating voltage falloff by a linear function in the amplifiers we tested.

Without directly observing the form of an amplifier's response beyond 1 s, one cannot determine with certainty what causes any given EEG amplifier to operate outside its prescribed specifications. In some cases, an amplifier circuit may not be a simple RC circuit as assumed, but have additional components, although this was not the case for the systems that we tested. One likely factor at play is that the capacitors seem to discharge more quickly than their ratings indicate. A second possible factor may be the exact implementation and shape of the bandpass filter underlying the LFF setting. For example, LFF = 0.01 Hz in one system may eliminate all frequencies below 0.01 Hz and attenuate some that are above 0.01 Hz. By contrast, the same LFF setting in another system may attenuate a few frequencies centered around 0.01 Hz, resulting in a practical shift in the actual LFF value that is applied to the signal. An effective low frequency cutoff (LFF) value being higher than the corresponding setting on the instrument would lead to the actual time constant being smaller. Even a relatively small change (0.001 Hz) in the actual LFF can have a significant impact on TC (LFF = 0.011 Hz, TC = 14.47 s vs. LFF = 0.01 Hz, TC = 15.92 s, using the analytic equation). Although we do not believe that the errors in filter LFF alone can be responsible for the dramatic discrepancies between the actual and the analytic TCs that we observed, they may be a significant factor in some systems. A third possible factor is circuit electronics polarization and saturation in response to a calibration train of positive pulses, which could create atypical decay curves and unstable trends in amplifier response. This factor would add to the signal an (up or down) sloping trend away from the baseline, and also would cause considerable variance in the rates at which the outputs of the different pulses decayed. We found that the averaging and sampling procedure that we describe below effectively compensated for the transient instabilities in amplifier response due to polarization.

Note that we do not intend to imply here that all commercial EEG systems necessarily exhibit the problems demonstrated by our experiments. It is not difficult, in principle, for a manufacturer to produce a system that compensates for amplifier distortions. Some manufacturers, in fact, do advertise AC systems that support DC acquisition. The aim of our report is purely to heighten awareness in the EEG/ERP community that issues with amplifier response can exist and when they do, they can generate serious problems for analysis of slow and DC potentials.

In sum, our experimental findings demonstrate that the filter characteristics in some commercial EEG amplifier systems may vary considerably across different channels with identical settings. Furthermore, filter response characteristics also can deviate substantially from the expected response based on manufacturer-supplied specifications. Clearly in such situations one must determine filter response characteristics *empirically* and *separately for each channel*.

Estimating Correction Factor

In this section, we discuss several points relevant to estimating a correction factor for systems in which amplifier characteristics deviate from the manufacturer's specifications. From the outset, we want to point out that estimating and correcting for amplifier distortions in this case is a nontrivial task. It requires a procedure that permits estimation of correction coefficients from very short (i.e., standard) square calibration pulses, which is generally extremely difficult. To the best of our knowledge, there is no easy universal solution to this problem that would suit all EEG amplifiers.

An obvious and unarguably preferable approach, provided it can be afforded, is to acquire amplifiers that output undistorted DC signals, either DC amplifiers or some of the newer AC systems that are designed to do this. However, in many cases, a new acquisition may not be feasible for various reasons. In such cases it may be possible to work around the problem. For example, one can modify the hardware by coupling an external pulse generator into the amplifiers to generate calibration pulses that are long enough to afford measurement of the filter parameters. An even better approach from an engineering perspective would be to add in a wobbled sine generator and measure the response output of each channel as a function of frequency. This solution would provide a direct measure of each channel's response no matter how complex the amplifier circuit.

Obviously, hardware modifications are also not practical for everyone. Moreover, there are likely to exist previously collected data sets for which standard square pulse calibration sequences provide the only characterization of the amplifier parameters with which the data were recorded. The only way to estimate TC for such data is from standard (i.e., short) square wave pulses. In the next section, we outline a procedure to help deal with such cases. We found the procedure to work well when amplifier output decline is linear, nearly linear, or can be assumed linear over some interval.

Before we present this procedure, we discuss reasons why empirical estimation of TC from short (standard) calibration pulses should be approached with caution, and why it is not at all a good solution when amplifier output follows a nonlinear falloff curve.

The question we consider here is empirical estimation of TC given only short duration calibration pulses. The duration of a calibration pulse in a typical EEG system amounts to less than 10% of the advertised amplifier TC when LFF = 0.015 Hz, and this percentage becomes smaller as LFF decreases. Once transients are eliminated from the pulse output, that percentage is cut in half. In the case of either the linear or nonlinear amplifier response, if the response is known to follow its theoretical functional form exactly, with no deviations and no noise built into the response, then an attempt can be made to estimate a single parameter response function from 5 to 10% of the response curve. However, as we illustrated above, even in the case of simple RC circuits, it is unlikely that the actual amplifier response will follow the theoretical falloff curve exactly. When the actual and the hypothetical functional forms of the response differ, it is impossible to estimate the true function parameters from only 5% of the actual falloff curve. Furthermore, it is unrealistic to expect exact, noise-free response from an amplifier circuit. Signals carried through EEG amplifiers contain noise, filter responses to square waves are characterized by significant transients, and, as we have shown here, amplifier responses fluctuate considerably.

The situation, however, is considerably easier when the amplifier response is linear. Even though the actual TC may differ from the theoretical value, the functional form of the response is known. We can use this piece of information to estimate output decay rate from short pulses, as shown in the next section. This is a crucial distinction between amplifiers with linear and nonlinear responses.

For single-stage RC circuit amplifiers, one can increase the probability that response is linear by dialing in an LFF setting at which the circuit response should be linear. In other types of circuits, the response falloff may turn out to be quasi-linear at least over some interval. In such cases, TC estimates can be calculated

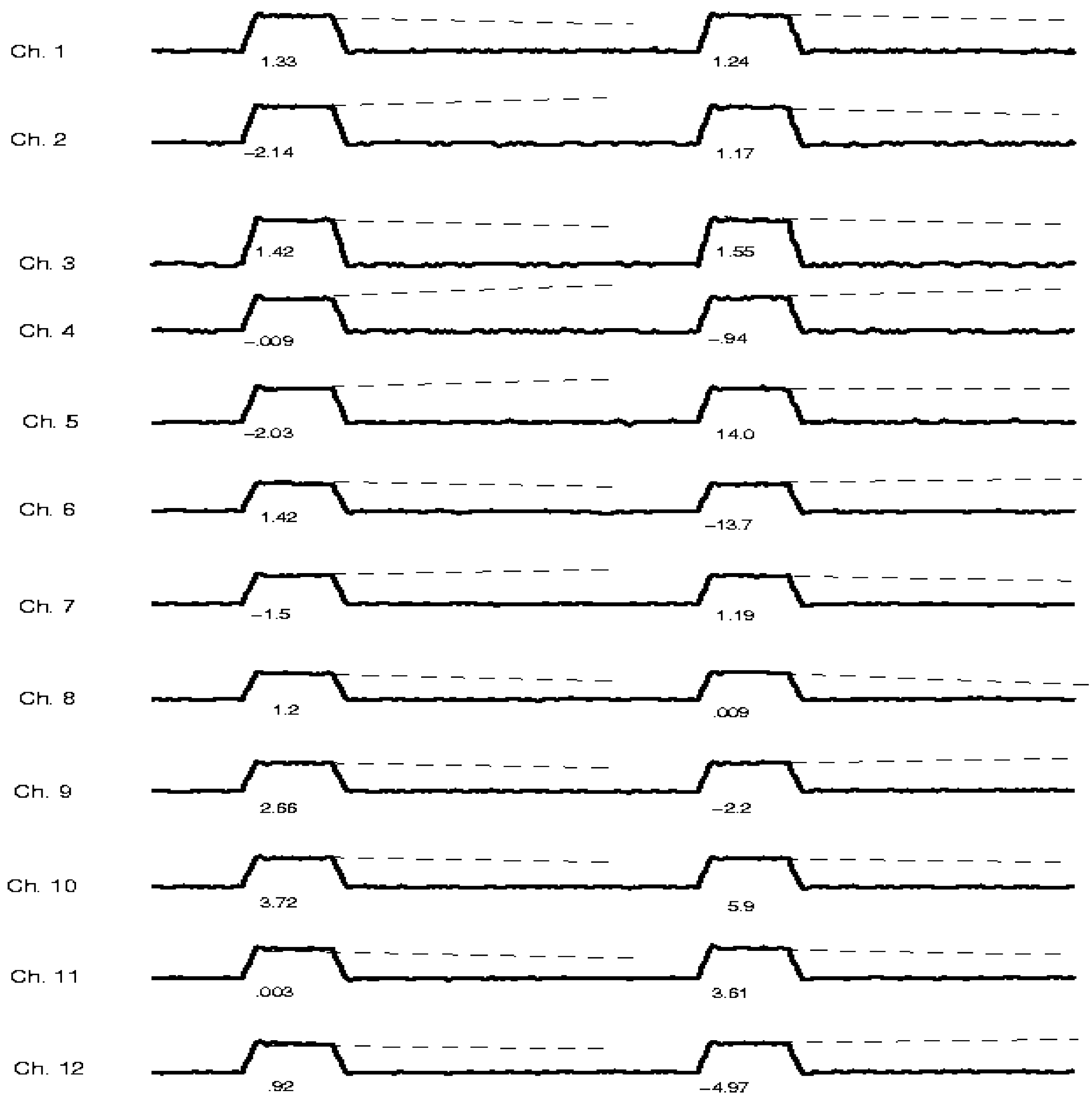

Figure 2. Variability of the TC within and across 12 channels. Under each pulse is the TC for that pulse calculated using the proposed method. Note that because of noise variability, it is possible to obtain a negative time constant measurement from a single pulse. For this reason, we calculate the time constants for many individual pulses and then use the median value across all of those pulses as our TC estimate.

using linear regression and applied to data within this interval. For example, in our EOG data characterized by DC waveforms up to 2 s in duration, the linear approximation to the falloff slope worked well for the 2-s intervals, and we were able to successfully correct for distortions using estimated TCs, even if there may be doubts as far as the shape of the entire falloff function in some of our EEG systems. This is an important point, as it may enable correction of amplifier distortions in cases of non-single-stage RC circuits.

Amplifier circuits characterized by nonlinear output curve include multistage filters and active filters. Although we are skeptical that one can estimate amplifier parameters from short calibration pulses when the output curve is nonlinear, if one wishes to estimate the parameters of a nonlinear response, we suggest a sampling and averaging procedure like the one described in the section below in order to obtain a stable estimate. We note that Gasser et al. (1982) attempted to estimate TC from calibration pulses when the output was nonlinear. Using the circuit diagram obtained from the manufacturer, they fit a nonlinear function defined by the circuit parameters to the output curve. The authors, however, appear to estimate the falloff function parameters from a single calibration pulse. Given noise in the circuit output and pulse-to-pulse fluctuations in amplifier response, such an approach seems unnecessarily risky.

Methods

Recipe for Computing Correction Factor

Below, we provide a recipe for estimating amplifier TC for the benefit of those who want to correct DC data for amplifier distortions. The recipe is written for the case in which the amplifier output falloff is linear. However, the linear regression step in the recipe can be replaced with a nonlinear estimate, if one desires, leaving other steps unchanged. The point of the recipe is not to teach the reader how to perform linear regression, but to demonstrate how one must sample pulse data and combine information from multiple calibration pulses to yield a stable and robust TC estimate. The sampling and averaging procedure we suggest may not be as trivial a point as it might seem. Our survey of published methods for estimating TC yielded only schemes that appear to estimate parameters from single pulses.

Theoretically, recovery of the original DC waveform from recorded data when amplifier output falloff is linear or close to linear is straightforward. According to standard RC circuit theory, the input voltage, $V_i(T)$ can be written as the output voltage $V_o(T)$ plus two correction factors. The first factor, $V_c(0)$, is a constant due to the residual charge carried by the capacitor before the start of our measurement. The second factor is the voltage due to the charge that accumulates on the capacitor of the AC amplifier circuit over the given time period ($\int_0^T V_o(t)\,dt$; see Elbert & Rockstroh, 1980; Ruchkin, 1993). The errors in measuring $V_o(T)$ are accounted for by adding an error term $e(T)$ to $V_o(T)$. Thus, given an output from a DC signal, such as an output from a calibration pulse, the input voltage can be recovered according to:

$$V_i(T) = V_c(0) + V_o(T) + e(T) + 1/\mathrm{TC}\int_0^T (V_o(t) + e(t))\,dt, \quad (2)$$

where TC designates the amplifier time constant as before. Hence, to estimate the left side of the equation, we must know the TC value for the amplifier, among other parameters.

Note that the constant $V_c(0)$ cannot be determined from measurements of the output voltage, although this does not present a problem, as this constant does not affect the shape of the voltage waveform, but only offsets it in amplitude. Therefore, we can recover the waveshape of the input voltage. The most notable effect of the measurement error $e(t)$ in Equation 2 is the constant trend in the output as the result of integration. This trend must be removed from TC estimates and from the $V_i(T)$ waveform calculations.

To estimate TC empirically, we must sample the output from a square calibration pulse in order to eliminate the large transients induced by square input, as these are unrelated to the circuit parameters that we aim to estimate (i.e., those controlling capacitor discharge). Circuit parameters estimated without the transients removed are inaccurate. A parameter estimate based on a single pulse also would be strongly affected by (potential) output fluctuation in that pulse. For all the systems we tested, a train of positive pulses did not charge and discharge any given amplifier in a consistent manner even over the course of a continuous calibration sequence. As a consequence, the TC values for individual pulse outputs are distributed in a bell-shaped curve with a few rather large outliers (see Figure 2 for sample pulses). For example, TC values estimated from individual pulses for a single amplifier circuit in the Nicolet SM2000 varied from 5.4 to 68.8 s. We believe the observed instability is an artifact of polarization induced by the pulse sequence, and thus would not be a problem in the case of fast varying EEG signals, which tend to oscillate around a zero axis. Nonetheless, one must contend with this artifact when estimating filter parameters from the calibration pulse data, as we outline next.

Outline of the Recipe for Empirically Estimating TC

For details on the procedure see the Appendix.

1. Before TC is computed, the amplifier/digitizer offset is removed from the calibration pulses (see Ruchkin, 1993, for a description of this artifact). This is accomplished by blocking the amplifiers for a short time and recording their output when the input voltage is zero.

2. Estimate TC for each square pulse in the calibration sequence, using the recovery slopes as shown in Figure 3. Here we suggest ignoring the initial (first) and final (fourth) quarters of each pulse, that is, using only the middle two quarters or 50% (bracketed by vertical lines in Figure 3), as output square pulses typically have large transients at the beginning and end of each pulse, which do not define circuit parameters that relate to the recovery of the amplifier and, in this case, only serve to obscure the estimate of these parameters. The middle 50% of each pulse was found experimentally to provide a stable estimate of amplifier recovery slope in all cases tested. We use linear regression to find the slope of the recovery. As already mentioned, one can substitute a nonlinear fit as needed.

3. The final estimate of the TC for a given channel is the median value of the individual pulse TC estimates. The median value is used instead of the mean because of the presence of extreme outliers in the distribution of the TC estimate.

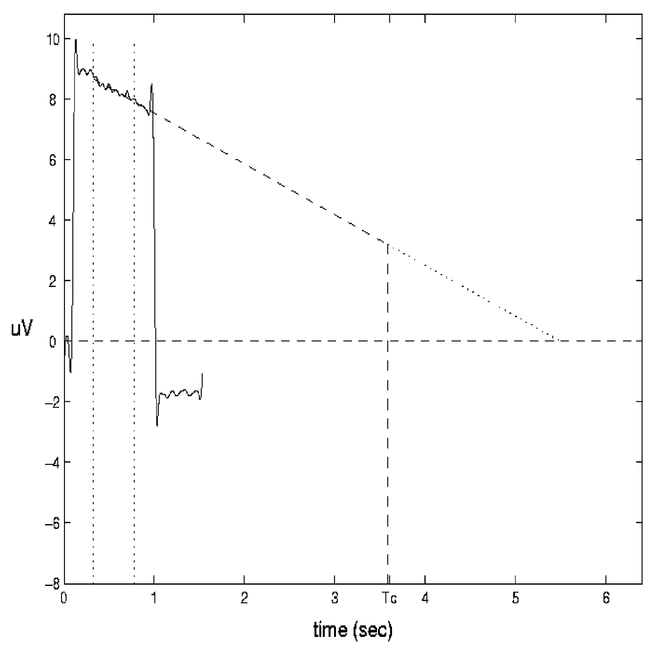

Figure 3. A calibration pulse marked for calculating the time constant (Horowitz & Hill, 1980). Vertical dotted lines show the interval during which the regression slope is calculated. Dashed lines show the extension of the regression line and the point that marks where the voltage amplitude reaches 37% of its initial value as estimated by the regression slope.

Additional steps may need to be implemented insofar as the calibration pulse generators introduce artifacts into the square pulse recordings. This can occur, for example, when a calibration box external to the EEG system is used to generate calibration pulses. These artifacts are specific to the calibration sequences, and thus are not present in EEG data recordings. Figure 4a illustrates 10-μV calibration pulses generated by an external calibration device; Figure 4b shows 20-μV internally generated calibration pulses. Note the overall downward ramp in the output signal in Figure 4a that is most noticeable in the interval (0 V) between the pulses. This trend is an artifact produced by the external calibration generator. The internally generated pulses in Figure 4b have no such ramp. Trends of this type generated by a calibration device will mask the constant amplifier/digitizer offset, and must therefore be identified and removed from the calibrated pulse output before the TC is estimated. To remove such artifacts from the calibration data, we suggest estimating the functional form of the artifact by fitting the mean values of the output voltage during the 0-V input intervals of the pulse sequence (i.e., in between the pulses) and subtracting this function from the amplifier output data. The constant amplifier offset then can be computed and removed as in first step described above.

Results

The procedure above was validated in a series of controlled experiments; it was found to yield consistent and robust correction in all cases. Figure 5 demonstrates the outcome of the linear correction procedure (Equation 2) applied to an ~6-s square pulse (solid line) using the linear correction factor from our method (dotted line), compared to that using the analytical TC estimate of Equation 1 (dashed line). Based on a high pass filter setting of 0.016 Hz, the analytical TC value was 9.95 s; the linear correction factor for the channel shown was 7.06 s. The linear factor, thus, allows us to

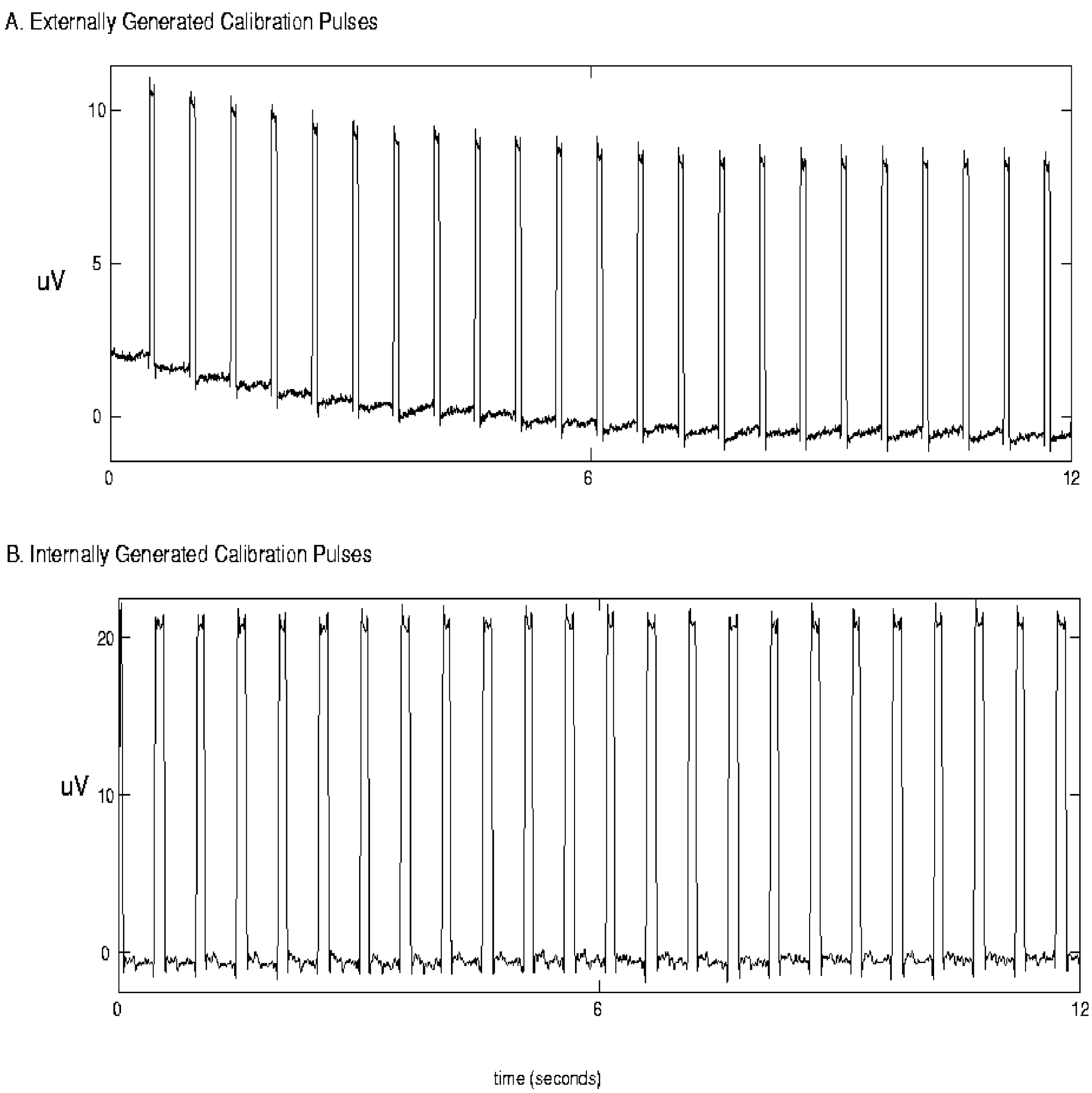

Figure 4. Ten-microvolt externally (a) versus 20-μV internally (b) generated calibration pulses. Note the overall downward trend in the externally generated pulses (a) that is an artifact of the pulse generator.

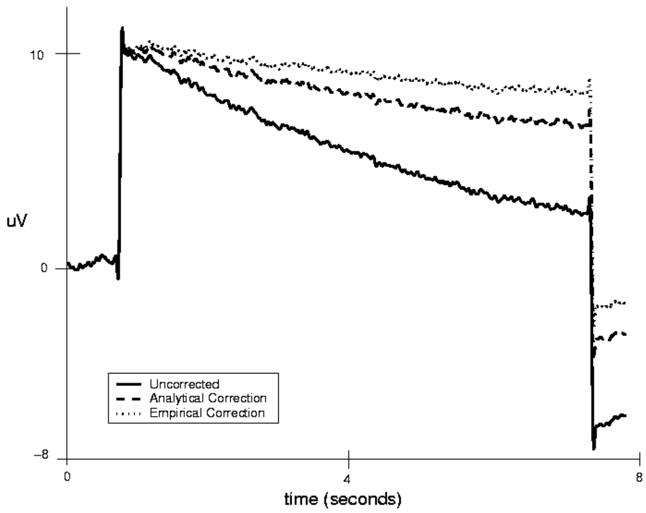

Figure 5. One 10-μV square pulse, approximately 6.3 s in duration. The pulse is shown as (1) the raw signal recorded from the amplifier (solid line), (2) DC-corrected using the theoretical time constant (dashed line), and (3) DC-corrected using the empirical time constant (dotted line).

recover a greater proportion of the slow potential signal than does the theoretical TC.

Discussion

This report illustrates that there can be significant discrepancies in the actual amplifier filter characteristics from those predicted analytically as well as considerable variations in these values across channels in the same EEG system, presumably housing identical circuitry. Under these circumstances, filter characteristics must be measured empirically for each channel of interest. Moreover, given that the capacitance may change over the years, this empirical check-up must be repeated periodically. Channels with extreme deviations can be identified and replaced; the output of others with less extreme deviations can be corrected with algorithms such as the one detailed herein. Indeed, the check also can be repeated across experimental sessions to take into account changing environmental conditions. As short calibration pulse data contain instabilities and deviations from the mean trend, we provide an effective recipe for estimating general filter characteristics.

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APPENDIX:
PROCEDURAL DESCRIPTION OF THE MEASUREMENT-BASED DISTORTION CORRECTION METHOD

1. Record ~100 calibration square wave pulses (approximately 200 ms in duration) for each recording channel.

2. Extract the calibration pulses from the raw data file with a prepulse interval of at least 100 ms.

3. Remove any artifacts due to calibration pulse generation:

   a. For each channel, compute the mean of the interpulse intervals across the calibration sequence.

   b. Using linear regression, calculate the slope across all interpulse means.

   c. Subtract the computed slope from the pulses recorded from the corresponding channel.

   d. Repeat for each channel.

4. Remove constant DC offset for each channel:

   a. Compute the average of all interpulse intervals for each channel separately.

   b. Subtract the value obtained in 4(a) from each pulse for the corresponding channel.

5. Estimate the time constants of all pulses across all channels:

   a. Disregard the initial and final 25% of each pulse (these contain transient noise created by pulse generators). Use the remaining, middle 50%, of each pulse.

   b. Fit a regression line to the selected segment of each pulse. Calculate the interval from the first point of the regression line to the point at which the regression function reaches 37% of its original value. The time constant is the number of data points in this interval divided by the sampling rate (data acquisition rate in points per second).

6. Obtain the final TC estimate by computing the median TC value for each channel from the samples found in 5.