Stimulus Artifact Reduction in Evoked Potential Measurements

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Objective: To investigate the main coupling mechanisms involved in stimulus artifact contamination of evoked potential recordings and to suggest techniques that minimize this interference.

Design: A before-after trial of a single subject.

Setting: Measurements were obtained at a university biomedical engineering laboratory.

Participants: Data were obtained from one volunteer subject.

Intervention: An electrical stimulus was used to depolarize the posterior tibial nerve at the ankle. Various recording electrode configurations were used to demonstrate stimulus artifact recordings.

Results: Three mechanisms are defined as contributing significantly to stimulus artifact contamination of evoked potential data. These are: the volume conducted component, the displacement current component, and the electromagnetic coupling component. When each component is maximally controlled, the problem of stimulus artifact is greatly reduced.

Conclusion: Three major factors that contribute to stimulus artifact contamination of the evoked potential waveform can be identified and minimized by relatively simple clinical techniques.

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Sensory Evoked Potentials (SEPs), as with most clinical electrodiagnostic procedures, are plagued with inherent electrical and other interference problems. An electrical depolarization pulse used to externally stimulate nerve tissue, contributes significantly to the recovered electrical noise. This particular type of interference is termed stimulus artifact (SA) because it is a nonpropagating transient (or remnant) of the stimulus pulse that appears as noise in the signal recordings. Stimulus artifact is not simply restricted to the duration of the stimulus pulse (generally 0.1 to 0.2 msec for peripheral nerve depolarization), but can extend into the time window of the evoked potential signal (tens of milliseconds) and can therefore contaminate the data. The research literature is limited in the area of stimulus artifact reduction. This is mainly because SA is coupled into the recording system in several ways, and these coupling sources are generally misunderstood. Figure 1 shows examples of spinal SEP data that have been contaminated with stimulus artifact. In the top trace, note that the artifact is still present and seems to be increasing as a slow wave at the onset of the SEP waveform. It is difficult to tell whether the waveform is biphasic or if there is an initial positive peak buried within the stimulus artifact. In the middle trace, the artifact does allow the initial positive phase of the waveform to be evident, but there is still some discrepancy as to where the waveform actually begins. The bottom trace, as with the top trace, has its initial positive phase masked by the artifact. Also, note a subtle trailing negative tail. This tail may be real (i.e., SEP) or may simply be a low frequency component of the stimulus artifact.

Although techniques to reduce SA are included in most standard textbooks of electrodiagnostic medicine, they are offered without scientific reason other than clinical experience. Sethi and Thompson¹ provide a relatively complete list of clinical practices that minimize stimulus artifact, the list, however, offers little insight into how to address the stimulus artifact in a systematic fashion. To the authors' knowledge, this article presents the first model of the causes of SA. Based on this model, it also presents clinical techniques that are invaluable in minimizing the effect of SA on SEP waveforms. The techniques are presented in terms of surface recorded spinal somatosensory evoked potentials; however, they generally apply to all clinical evoked potential recording situations.

LITERATURE REVIEW

McGill et al, in 1982,² published the most complete account to date of the causes of stimulus artifact, and described techniques for its reduction. The researchers identified the problem as having several contributing factors, including the type of stimulator used, the type of electrodes used, the skin preparation under each electrode, and the characteristics of the recording amplifier. Kornfeld in 1985³ suggested that the artifact might also be affected by electrode orientation. Daube⁴ suggested that more attention be paid to the placement of the ground electrode to control stimulus artifact in sensory nerve conduction studies. He suggested that correct ground electrode placement would eliminate conducting bridges between ground and the stimulating electrodes and, thus, stimulus artifact; however, no indication is given regarding appropriate placement of the ground electrode. He also suggested that the stimulating and recording electrode orientations could affect the magnitude of the stimulus artifact, again without the provision of specific details.

Spencer⁵ and Knafflitz and Merletti⁶ focused on the characteristics of the stimulator to reduce stimulus artifact and concluded that "constant current" stimulators (or high impedance stimulators) are preferable for evoked potential studies. Constant current stimulators possess high output impedance and thus decrease the amplitude of the stimulus artifact caused by electrode capacitive discharge (especially for narrow stimulation pulses). This does, however, cause the remaining stimulus artifact to last much longer than that of a "constant voltage" stimulator, and the stimulus current tends to be less comfortable for experimental subjects. A constant voltage (or low impedance) stimulator provides a low impedance path for discharging electrode capacitances and thus causes a relatively short-lasting artifact.
transient. The amplitude of this transient, however, may be large enough to saturate the recording amplifiers, which in turn causes more signal distortion. More recently, stimulation systems have been designed to switch from constant current output during the stimulus pulse to constant voltage between pulses to reduce the amplitude of the artifact while also limiting its duration.

Others have worked on the recording system to prevent stimulus artifact from appearing in evoked potential data. Recording amplifiers have been designed to record nothing until the stimulus artifact has finished in order to avoid saturation. This technique has been largely unsuccessful because of further noise introduced into the system by the added instrumentation.

Discussions of evoked potential setup generally include the use of a ground electrode, minimization of lead length, the use of "nonpolarizable" electrodes for the recording system as well as the use of constant-current stimulation, and stimulus artifact blanking schemes as means to reduce stimulus artifact. These common methods of stimulus artifact are valid techniques, and some will be discussed with reference to the model described in this report. Some authors suggest the use of a ground electrode placed between the stimulus and the recording electrode. Chu-Andrews suggests that this ground electrode be placed closer to the recording electrode. We studied this practice and concluded that the best location for the ground electrode is midway between the stimulus and the recording electrodes.

The objective of this work was to create a model that describes the phenomenon of stimulus artifact. In this model, the major causes of the artifact are identified such that they can be dealt with in the clinical setting. The new understanding of the mechanisms involved in stimulus artifact generation offers a means for the clinician to determine the likely source of the artifact and to address the particular coupling mode by specific reduction strategies. Other work to design a system that filters the stimulus artifact from evoked potential systems while not interfering with the signal waveform (nonlinear adaptive noise cancellation) is ongoing at our center and elsewhere, and also proves helpful in situations in which the techniques discussed here may not adequately reduce the problem. Discussion of these techniques is beyond the scope of this report.

THE STIMULUS ARTIFACT MODEL

Three major components of stimulus artifact are: (1) volume conducted current; (2) displacement current; and (3) electromagnetically coupled current. The total stimulus artifact in evoked potential data is the linear sum of these three effects.

The Volume Conducted Current

When current is passed through any medium, it spreads throughout the full extent of that medium. The current flows from the positive to the negative electrode, but does not always take the shortest path. The current density is greatest at points near to either electrode, and is smallest midway between them (fig 2).

Stimulus artifact arises from this current flow because of the potential difference it creates at the recording electrodes. If the recording electrodes are not placed exactly along equipotential lines, the remnant of the stimulus pulse at the recording electrode sites will be collected with the evoked potential data.

In 1985, based on this principle, Kornfeld suggested that recording electrodes be placed along equipotential lines with respect to the current flow. If the recording electrodes are not placed precisely along the same equipotential line, the stimulus current will cause a potential difference to be seen at the input of the preamplifier and will therefore exist in the data. The stimulus artifact caused by the volume conducted current may be drawn from arbitrarily small potential differences. It is difficult to know exactly where these equipotential lines are in an experimental situation, as the field equipotential lines are modeled for a circular or cylindrical tissue medium. Humans do not provide this simple geometry. What is important to consider is the direction of the equipotential lines at any recording site, to permit the clinician to minimize the effect of these small potential differences on the total stimulus artifact. This practice is further confounded by the fact that the equipotential lines of the stimulus current may shift somewhat during the stimulus pulse due to its frequency-dependent nature. The square-wave pulse used for stimulation is actually comprised of a set of sinusoid current waves of varying frequencies, and thus the different frequencies that dominate at particular points of the stimulus will vary. This means that the equipotential lines, whose location varies with the stimulus pulse frequency, will shift during the stimulus pulse.

To isolate the volume conducted component of the stimulus artifact for illustration purposes disposable Ag-AgCl electrodes were used for both stimulation and recording. Skin preparation included cleansing with alcohol, abrading it with...
The preamplifiers used for all recordings were designed by Lovely to have very low noise, and common mode rejection exceeding 100 dB. The overall bandwidth of the recording system was 25 Hz to 1 kHz, appropriately including the frequency spectrum of a spinal SEP, and, unfortunately, the SA. As evident from figure 3, the volume conducted component of the stimulus artifact will be most evident with the electrode configuration described above. When the positive and negative electrodes are placed lateral to each other, the chance is slight that they are on the same equipotential line with respect of the volume conducted component of the SA. Typical results are presented in figure 4.

Note in figure 4 that the peak-to-peak amplitude of the stimulus artifact is $3.5 \times 10^{-4}$ volts at 30 cm from the stimulus, and it decreases to $1.5 \times 10^{-5}$ volts at 60 cm from the stimulus. Doubling the distance from the stimulus decreases the amplitude of the stimulus artifact by a factor of 23. These results indicate that an effective mechanism for minimizing the volume component of the stimulus artifact is simply to maximize the longitudinal separation between stimulating and recording electrodes.

Other possibilities to minimize the volume conducted component would be to minimize the lateral spacing between the positive and negative measuring electrodes (which would decrease the potential difference due to electrodes being placed on different equipotentials with respect to the stimulus current) or, as previously noted by Kornfield, to attempt placement of the recording electrodes along the same equipotential line with respect to the stimulus current. Unfortunately, in human experimentation scenarios, the electrode orientation is often determined by other considerations such as limb geometry and the anatomic location of the structures of interest. Whenever possible, however, the maintenance of maximal distance between stimulus electrodes and recording electrodes, and the placement of recording electrodes as nearly on equipotential lines as possible, should be the practice. Changing the orientation of the stimulus electrodes is another option; however, the stimulating electrode location is even more stringently tied to the anatomic arrangement of tissues at the stimulus site. Although the nerve may be depolarized by placing the cathode directly over the nerve, and the anode at any other location, it is our experience that certain electrode configurations (in particular, the one described above) are more comfortable for the subjects, and that these same configurations produce better quality SEP signals. This is likely due to the ability to increase the stimulus to a higher voltage while maintaining subject comfort. Since the ultimate goal of the work is to produce better quality SEP signals, the stimulus electrode orientation is best kept as one that maximizes the amplitude of the SEP signal, and the stimulus artifact be dealt with at the recording end of the system.

![Fig 3. Placement of recording electrodes on equipotential lines with respect to the stimulus current. Note that the equipotential lines (- - - - -) with respect to the volume conducted current (- - -) run essentially caudo-rostrally for the stimulus electrode configuration used in this study. These equipotential lines would change in orientation with a different electrode configuration but could be estimated using the theory presented.](image)

![Fig 4. Volume conducted component of stimulus artifact (A) measured at 30 cm from the stimulus, and (B) measured at 60 cm from the stimulus. A recording electrode configuration aimed at maximizing the volume conducted component of the stimulus artifact was used. (Note 40x scale change between A and B.)](image)
Displacement Current

Despite all attempts to isolate the experimental subjects from all electronic instrumentation, perfect isolation is not possible. Most, but not all, current follows the path of least resistance. Since current ultimately flows toward ground (or zero potential), most current flows from the positive to the negative stimulating electrode. Some current, however, escapes to other paths, despite the larger resistance to these paths. This is due to the current divider effect, illustrated in figure 5. In this figure, \( Z_l \) is the resistance in the stimulator, \( Z_e \) is the resistance between the positive and negative stimulating electrodes, \( Z_d \) is the resistance between the stimulating electrodes and alternative current paths through the body to ground, and \( V \) is the voltage output of the stimulator. The total current in this system (\( I_{\text{total}} \)) is determined as

\[
I_{\text{total}} = \frac{V}{Z_l + \left( \frac{Z_e Z_d}{Z_e + Z_d} \right)}.
\]

\( I_{\text{total}} \) is then used in the determination of the "displacement current" as

\[
I_d = I_{\text{total}} \left( \frac{Z_e}{Z_e + Z_d} \right).
\]

Since \( Z_e \ll Z_d \), only a small amount of the total current follows a capacitively coupled path to ground. Most of the current simply flows between the stimulating electrodes as desired. It is the capacitively coupled current path to ground that contributes to the displacement current component of the stimulus artifact. This current flows from the stimulating electrodes, along the stimulated limb, and through the subject's body until finding a ground path. Figure 6 shows how the displacement current is dispersed throughout the subject's body.

For an experimental illustration of the displacement current component of the stimulus artifact, the stimulating and measuring parameters were kept consistent with those used in illustration of the volume conducted component. In this instance however, the output potentiometer of the SIU was set to zero to ensure that no volume conducted component of the stimulus artifact was present in the traces (as no current would flow through the tissue volume). The recording electrode orientation was also changed to maximize the displacement current component of the stimulus artifact. Since this current flows from distal to proximal, the equipotential lines were now similar to the current path of the conducted current component and at right angles to the equipotential lines of the volume conducted component. As such, the positive electrode remained at the midline; however, the negative electrode was placed 5cm distal to the positive electrode, and the reference electrode (for consistency) was placed 5cm lateral to the negative electrode. The recorded stimulus artifact is shown in figure 7. Note that in the case of the displacement current component, an increase in distance from 30 to 60cm from the stimulus site produces a decrease in the peak-to-peak amplitude of the stimulus artifact by a factor of 2. Although this experimental setup maximally isolates the displacement current component of the artifact, the decrease in the artifact with increasing distance likely results mainly from volume conducted current that is still present in the recordings. Theoretically, the displacement current should not attenuate with increasing distance from the stimulus site.

There are limited means of minimizing the displacement current component of the stimulus artifact. The magnitude of the displacement current is determined by the capacitance through the SIU to ground, and by the subject's body capacitance to ground. It is unfeasible to alter the SIU to improve this scenario.

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**Fig 5.** The current divider effect. The total current (\( I_{\text{total}} \)) resulting from the voltage source (\( V \)) (stimulator) and the total impedance (impedance at stimulator output \( Z_l \), impedance of the tissue between electrodes \( Z_e \), and impedance of the other current paths to the ground \( Z_d \)) divides at point \( X \). The current that passes between the stimulating electrodes (\( I_e \)) is equal to \( I_{\text{total}} \) multiplied by the ratio \( Z_e/(Z_e + Z_d) \).

**Fig 6.** Schematic representation of the displacement current that contributes to the overall stimulus artifact. The displacement currents flow from either stimulating electrode through the body and to ground from whatever low impedance paths can be found.

**Fig 7.** Displacement current component of stimulus artifact. (A) The stimulus artifact at 30cm from the stimulus site and (B) the stimulus artifact at 60cm from the stimulus site were recorded using electrode configurations aimed at maximizing the displacement current component of the stimulus artifact. Note that the displacement current remains essentially the same for increasing distances from the stimulation site.
and difficult to make significant changes to the body-to-ground capacitance. The use of a ground electrode placed on the limb between the stimulating and recording electrodes is the best solution. This will essentially short-circuit the stimulation-induced displacement current to ground before it reaches the recording electrode sites. Ideally, the ground electrode should encircle the limb. This will maximize its current sink effect more so than a single ground electrode placed on the limb at the same site and produces no increased risk to the subject, as well as minimal increased setup time for the clinician. This technique will not cause total elimination of the artifact (as suggested by McGill et al) but will greatly reduce it. Figure 8 shows the effect of a ground electrode placed between the stimulating and recording electrodes. For this illustration, the same stimulation and recording parameters were used as in the previous two examples, with the stimulator output set at 70V and the SIU output set at 16. This stimulation level is typical of that used for experimental SSEP measurements.

Measuring electrodes were placed in two locations, one at the gluteal fold (over the sciatic notch) on the left lower limb, and one at L2 spinous process. The gluteal fold electrode configuration placed the positive electrode over the sciatic notch at the gluteal fold, the negative electrode 5cm lateral to the positive electrode, and the reference electrode 5cm distal to the negative electrode. At the L2 site, the positive electrode was placed at the L2 spinous process, the negative electrode was placed 10cm lateral to the positive electrode to the left, and the reference electrode was placed at 10cm lateral to the positive electrode to the left. Traces of the stimulus artifact were obtained for four scenarios. The letters a and e show the stimulus artifact with no ground electrode in use, b and f show the recovered stimulus artifact when a ground electrode was placed at the upper thigh, c and g show the recovered stimulus artifact with a ground electrode placed at the knee, and d and h show the recovered artifact when a ground electrode was placed at the left ankle. The ground electrode in this study was a cotton skate lace soaked in electrode paste (Sigma Creme). Skin preparation was done prior to placement of all electrodes.

Note that a ground electrode encircling the limb has a major effect on the stimulus artifact. At the sciatic nerve measuring site, this effect is greatest with the ground electrode placed at the knee. In contrast to Chu-Andrews, it is postulated that this middle location is better than that of the upper thigh because, with the ground located in close proximity to the recording electrodes, any current that escapes this path to ground will be concentrated at the ground strap location and, therefore, will cause an apparent increase in stimulus artifact in the signal recordings. At the L2 measurement site, there is little difference between placing the ground strap at the knee or at the upper thigh, because the recording site is at a sufficient distance from the ground strap in either case. Generally, the researchers have found that the best location for the ground strap is at a distance midway between the stimulating and the recording electrodes.

A major consideration in using a ground electrode is that of electrical safety with respect to power line electric shock because this method involves a direct, deliberate connection of the subject to ground. The stimulus isolation unit and the isolated preamplifiers used in biopotential measurements are designed to ensure that the subject is not connected to ground, specifically for the purpose of electrical safety. With no intentional ground connection, the scenario that must occur to produce an electric shock involves, with the stimulator as the source, the coincidence of three events: a line-to-input fault in the stimulator, an input-to-output fault in the SIU, and a subject-to-ground connection. The likelihood of an accidental subject-to-ground connection is by far the greatest of the three events (a subject accidently touching the instrumentation rack would constitute a subject-to-ground connection). Electrical standards are actually calculated assuming an accidental connection to ground, and are deemed sufficient. In any event, the joint probability of the other two events occurring simultaneously is the product of their individual probabilities, which is extremely small. Similarly, for electric shock to occur due to faults in the measuring system, with the subject intentionally grounded, it is still required to have coincidental faults: a line-to-input fault in the amplifier, and an input-to-output fault in the isolated preamplifiers. Again, the joint probability of these two events is extremely small. It was decided that, for the purpose of this work, the use of a ground connection would not add significant risk of electric shock to the subjects; therefore, this practice was adopted for all evoked potential measurements.

Another method to minimize the displacement current component of the stimulus artifact would again be to place the recording electrodes along an equipotential line, this time with respect to the displacement current. In this case, the equipotentials will nearly be at right angles to those caused by the stimulus current. Because the volume conducted component of the stimulus artifact is minimal at greater distances from the stimulus, as is the case for the typical SSEP measurement setup, attempts should be made to place the recording electrodes on the equipotential lines with respect to the displacement current.

Electromagnetic Coupling

The final component of stimulus artifact is the electromagnetic coupling that occurs as a result of imperfect shielding between stimulating and recording electrodes and leads. Standard lead shielding is about 20% effective and thus allows for the capacitive coupling of the stimulus current to the recording system. Modern instrumentation systems have extremely high input impedances, which reduces the magnetic field coupling component of the stimulus artifact. However, if very high impedance measuring electrodes are used, electric field coupling...
occurs, and the capacitance between stimulating and recording electrodes and leads can contribute significantly to the total stimulus artifact. (Low impedance electrodes, on the other hand, have a minimal capacity to build up charge at the electrode-skin interface, and thus there is minimal charge coupling between the stimulating and recording electrode-skin interfaces.) Figure 9 illustrates the mechanism of electromagnetic coupling of the stimulus artifact into the recording system.

Minimizing the electromagnetic coupling component involves the use of well-shielded leads, which have been shortened as much as possible. Contrary to Chu-Andrews, leads may be intertwined among themselves. Stimulus and recording leads should be kept as far apart as possible during the measurement session, large loops should not be present, and low impedance electrodes with adequate skin preparation should be used whenever possible. Low impedance surface electrodes (Ag-AgCl) have been used with much success and are less invasive; however, needle electrodes would produce another option if required. The effect of electromagnetic coupling is illustrated in figure 10 in terms of the electric coupling between stimulating and recording electrodes. For the purpose of this work, the stimulating and recording parameters were kept as in figure 6, with the stimulator set at 70V and the SIU set to 0. The recording electrode locations remained consistent at the sciatic notch (A and B) and at the L2 spinous process (C and D).

There is an obvious reduction in the amplitude of the stimulus artifact at both sites (sciatic nerve and L2 spinous process) using low impedance electrodes. The residual artifact is attributable to the displacement current effects.

**DISCUSSION**

Clinical techniques to reduce stimulus artifact should be employed in all SEP measurements, due to its potential contamination of the waveform data. The conceptual model of the stimulus artifact, including the volume conducted component, the displacement current component, and the electromagnetic coupling component, provides a clear picture as to the causes of the artifact and, thus, enables the researcher to maximally limit each component in sequence. Instrumentation alterations to both the stimulator and the measuring system may also be of some value, but this is beyond the ability of most clinicians. As postprocessing techniques become more developed, they will likely be of great value, however, these techniques have yet to be perfected. If the researcher is looking for waveform characteristics, it is prudent to avoid these postprocessing techniques until he or she can be convinced that the adaptive filtering process employed does not alter the SSEP waveform characteristics in any way. The proposed model is presented in figure 11.

The coupling mechanisms discussed by the model are functions of the stimulus amplitude and duration. Because these parameters are determined by the physiological system, the techniques for reduction of stimulus artifact do not include the use of altering these parameters. That said, use of the lowest possible amplitude of the stimulus pulse that produces the desired physiological response will minimize the amplitude of the stimulus artifact to some extent. A difference in the order of 0.1 to 0.2msec duration of the stimulus pulse does not significantly affect the stimulus artifact in the recovered signals. The waveshape of the pulse also plays a role in the stimulus artifact, but this again is usually limited by the physiological system in terms of subject or patient comfort and the elicitation of a response.

Adequate skin preparation has been discussed in terms of minimizing the polarizability of the electrodes, thus reducing the electromagnetic coupling component of the SA. If a subject...
perspaires heavily under the electrodes, this should not adversely affect the stimulus artifact; in fact, it should again reduce the polarizability of the electrodes, unless the amount of perspiration is sufficient to increase the conductivity over the skin surface. (In this situation it is recommended, in accordance with Sethi and Thompson that the skin be wiped with a cloth that has been dampened with alcohol before data collection begins.)

If the skin preparation is omitted, however, the presence of skin cream or oil, or even just dirt and dead epithelial cells beneath the electrodes will increase the amount of SA recovered because of the resulting increase in electromagnetic coupling (by increasing the impedance of the electrode-skin interface). Simply stated, a skin preparation regime of cleaning, abrading, and massaging of electrolyte paste should be done under each electrode. Skin creams and oils, as well as perspiration at other locations of the skin surface, should not be a problem provided that the areas under study have been adequately prepared prior to the application of electrodes.

**CONCLUSION**

The three components of stimulus artifact have been presented as the volume conducted current, the displacement current, and the electromagnetically coupled current. Each component can be isolated in the experimental setting, and thus can be dealt with separately. The volume conducted component of the stimulus artifact is best minimized by maintaining as much separation as possible between the stimulating and recording electrodes. Increasing the distance between the electrodes by a factor of 2 will cause a decrease of the stimulus artifact amplitude by a factor in the order of 20. The recording electrodes are best placed along equipotential lines of the displacement current component, as this component does not attenuate with increasing distance from the stimulus site. The use of a ground strap is encouraged when the clinician is confident that there is limited increase in risk to the subjects, because this will reduce the displacement current component of stimulus artifact by a factor of 5 or more. The electromagnetic coupling component of stimulus artifact poses less of a problem in the signal recordings; however, it has been shown that the use of nonpolarizable electrodes (such as Ag-AgCl) with appropriate skin preparation can reduce the artifact by a factor of 5 or more as well, when compared to the use of stainless steel electrodes over dry skin. These techniques may not eliminate the stimulus artifact completely, but it has been found that their use will produce SEP data that are not contaminated by stimulus artifact transients.

**References**


**Suppliers**

a. Catalog Number 2259 Red Dot® disposable Ag-AgCl monitoring electrodes; 3M Canada, Ltd., London, ON, Canada N6A 4T1.

b. Sigma Creme® Electrode Cream; Parker Laboratories Inc., Orange Hill, NJ 07050.

c. Grass SI; SIU8T6; Grass Instrument Division, Astro-Med® Inc., Astro-Med Industrial Park, West Warwick, RI 02893.