Electron transfer processes occurring on platinum neural stimulating electrodes: a tutorial on the $i(V_e)$ profile

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Abstract
The aim of this tutorial is to encourage members of the neuroprosthesis community to incorporate electron transfer processes into their thinking and provide them with the tools to do so when they design and work with neurostimulating devices. The focus of this article is on platinum because it is the most used electrode metal for devices in commercial use. The $i(V_e)$ profile or cyclic voltammogram contains information about electron transfer processes that can occur when the electrode-electrolyte interface, $V_e$, is at a specific potential, and assumed to be near steady-state conditions. For the engineer/designer this means that if the potential is not in the range of a specific electron transfer process, that process cannot occur. An $i(V_e)$ profile, recorded at sweep rates greater than 0.1 mVs$^{-1}$, approximates steady-state conditions. Rapid transient potential excursions, like that seen with neural stimulation pulses, may be too fast for the reaction to occur, however, this means that if the potential is in the range of a specific electron transfer process it may occur and should be considered. The approach described here can be used to describe the thermodynamic electron transfer processes on other candidate electrode metals, e.g. stainless steel, iridium, carbon-based, etc.

Keywords: electrochemistry, platinum, neural stimulation, neural prostheses, electron transfer processes, oxidation, reduction, cyclic voltammetry

(Some figures may appear in colour only in the online journal)

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Foreword by J Thomas Mortimer

Understanding the electron transfer processes for neural stimulating electrodes could, and I expect would, expand the creative opportunities for engineers working in, or interested in entering into, the field of electrical activation of the nervous system: it did for me.
Over the time of my career, now approaching five decades and with six neuroprostheses behind me, I (beginning as an electrical engineer) have acquired an understanding of the electron transfer processes taking place on platinum neural stimulation electrodes. Platinum or platinum–iridium alloys are the most commonly used metals for current injection into living systems. The first step in understanding the electron transfer processes occurring on platinum neural stimulation devices is to understand the \( i(V_e) \) plot, aka cyclic voltammogram (CV). The \( i \) is the measured current flowing across the electrode–electrolyte interface as a function of the voltage across the interface, \( V_e \). The \( i(V_e) \) plot informs the observer about the electron transfer processes that are possible under equilibrium conditions:

\[ i(V_e) = \begin{cases} 
\text{negative potential raises Fermi level} \\
\text{positive potential lowers Fermi level} 
\end{cases} \]

The main point to get from this statement is that reactions can only occur if \( V_e \) is in the potential range where the reaction can occur, but, because of kinetic limitations on the transfer processes, may not occur under neural stimulation conditions.

I have learned that the platinum \( i(V_e) \) plot can be understood and it is not as scary as it may first seem. It is that understanding that I want to bring to our community with the hope that engineers will find the explanation presented here more approachable than that found in textbooks.

**The purpose of the neural stimulating electrode**

The purpose of the neural stimulating electrode is to set up an electric field that will trigger the opening of voltage-gated sodium ion channels along some portion of an axon. If the stimulus (i.e., induced electric field) is strong enough, the triggered opening will result in a propagated action potential that will cause the release of a neurotransmitter at the end of

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6 (1) Employing platinum electrodes: dorsal column stimulator for pain suppression, bladder and bowel assist device for spinal cord injured subjects, and a visual prosthesis applied to optic nerve for blind subjects and (2) employing stainless steel electrodes: hand assist device using percutaneous electrode in spinal cord injured subjects, paraspinal muscle stimulation using percutaneous electrodes for subjects with scoliosis, and a diaphragm pacing device with electrodes implanted in the diaphragm for subjects with spinal cord injury and more recently subjects diagnosed with ALS.
The electric field is set up in the tissues containing the axons by causing ions to move, positively charged in one direction, and negatively charged in the opposite direction. These ions are caused to move by injecting/electrotransferring electrons into a conducting solution from a metal, platinum in our case, through wires and electronic circuitry connected to a charge storage device such as implantable pulse generator. Generally speaking, a cathodic pulse is preferable because it requires less charge to create propagated action potentials than does an anodic pulse. For this reason, most devices deliver a cathodic pulse to initiate action potential propagation. It is important to recognize that electrons do not spew out of the electrode into the tissue during a cathodic pulse; rather (1) electrons either build up on the metal, and positively charged ions move nearer to the metal surface to supply a counter charge (non-faradaic double layer charging), or (2) electrons are transferred from the electrode to a reactant at the electrode surface, (faradaic electrochemical reduction reaction). During an anodic pulse, the reverse of these two processes can occur. Non-faradaic charge transfer is synonymous with the charging/discharging of the double layer on an electrode and is a completely reversible, capacitive reaction. Faradaic charge transfer always involves the exchange of electrons between the electrode and a reactant in the tissue. Faradaic reactions can be either chemically reversible or irreversible, depending on the electrode material and the reactants involved. Electron transfer across the electrode–tissue interface may give rise to molecules that can have harmful effects, such as metal loss from the electrode and/or biological cell damage. If we understand what reaction products are created during electrical stimulation, we have a better chance to design devices that can inject more charge while controlling the generation of undesirable reaction products. Our aim here is to provide the neural prosthesis community with tools and insight into how these electrodes operate.

**Figure 2.** Quantum theory of an atom states that only certain energy states for an electron are allowed and these are quantized. To transfer an electron from one medium or molecule to another medium or molecule, the electron energy of the transferred electron must be identical to that of the allowed unoccupied state of the other; otherwise, radiation would be required to account for the energy difference. In the hypothetical case of a single molecule shown on the left panel, the electron states are filled to a certain energy level (highest occupied molecular orbital, HOMO) and the next possible energy level is unoccupied (Lowest unoccupied molecular orbital, LUMO). If this molecule were sufficiently close to a metal electrode and the Fermi Level of the electrons in the electrode was elevated to the same level as the unoccupied energy state (LUMO) of the molecule, an electron could move from the electrode to the unoccupied state of the molecule (right panel). In this manner, current applied to an electrode can alter the ionic state of the molecules in the vicinity of the electrode. It is also worth noting that electron transfer does not occur for lower energy levels because the allowable states in the metal and that of the molecule are full at the matched energy level.
have a maximum of two electrons, spin up and spin down. In the ground state, the orbitals are filled progressively from the lowest energy to the highest. In a metal, the conduction electrons are in the partially filled valence band and behave as an electron gas, each with different energy levels and not associated with any specific atom. In this free electron model of metals, electrons are still constrained to have discreet and distinct energy levels starting at the lowest occupied state and filling to the highest occupied state. Above this last state is the lowest unoccupied state. The highest occupied level at absolute zero, 0 K, is defined as the Fermi level. At temperatures above 0 K, electrons can occupy higher energy levels; however, for this discussion the Fermi level is treated as the highest energy level for electrons in the conduction band. This approach to describing electron transfer between electrodes and electrolytes is known as a Gerischer–Marcus model and is based on work by Heinz Gerischer [2, 3] and Marcus [4]. It has been further described by Bard and Faulkner [5].

A distribution of energy states within a metal is depicted as an arbitrary curve in figure 1. The horizontal line through the curve denotes the Fermi level, which is the highest energy level occupied by electrons in the metal at 0 K. The Fermi level at body temperature is assumed to be essentially the same as at 0 K. At energy levels below the Fermi level, all energy states are occupied. The center panel of figure 1 illustrates the filled and vacant electron states for a hypothetical metal at a rest or zero current potential. When electrons are added to the metal, a negative potential applied between the metal of interest and a counter electrode elsewhere in the system, the energy levels of all electrons in the conduction band are elevated, and the Fermi level rises. When electrons are removed from the metal, a positive potential applied, the energy levels of all electrons are lowered, and the Fermi level is lowered. Figure 1 illustrates an energy profile for an arbitrary conduction band in a metal, and the associated Fermi levels at states of lower energy (positive potential applied), and higher energy (negative potential applied). Energy levels are referenced to the vacuum level, which is the energy an electron would have if it were displaced an infinite distance from the nucleus.

Figure 2 presents a hypothetical case of a single molecule in close proximity to a metal. In the resting state, the Fermi level of the electrons in the conduction band is higher than the occupied states of the single molecule and lower than the unoccupied states of the single molecule (see left-hand panel). For electron transfer to occur, the highest energy of the electron in the metal and the energy of the unoccupied state of the metal must be at equal energies, otherwise radiation energy would have to be given off; this is radiationless electron transfer. The right hand panel illustrates the elevation of the Fermi level by the application of a cathodic current. When the Fermi level of the metal is identical to the energy level of the unoccupied state of the single molecule,
electron transfer can occur from the metal to the molecule, giving rise to a molecule in a valence state that did not previously exist.

If an anodic current were applied to the metal, the Fermi level could be decreased to a level where an electron transfers from a single molecule to the metal, again resulting in a molecule with a valence state that did not previously exist.

The central point here is that electrons can be transferred between the metal and molecule only when the Fermi level of the metal is raised or lowered to a level that aligns with the available energy states of the molecule.

Moving from a model of electron transfer between an electrode and a single molecule to a model of an electrode–electrolyte interface, we need to think in terms of the probabilities of electron transfer as a function of energy level. The model of an electrode–electrolyte interface takes into account: (1) the interaction of water in the electrolyte with the reactant, (2) electron transfer that can require electron orbital rearrangement of the reactant, and (3) the concentration of the reactants. The left-hand panel of figure 3 shows the single molecule model and the right-hand panel shows the probabilistic model. $N(E)$, aka density of states (probability of a reactant having a donor electron or an acceptor state available at an energy level $E$), has been introduced to account for the probability that the reactant will have an energy $E$. The probability of electron transfer increases as the Fermi level is elevated for transfer to an acceptor or oxidized state or lowered for transfer from the donor or reduced state. The tails of the distribution are energy regions where the probability is lowest.

As the concentration of reactants at the electrode–electrolyte interface is increased, the probability of finding a reactant at a specific energy level increases (see figure 4).

Acceptor and donor states can be created by reactions occurring on the electrode–electrolyte interface. When an anodic current is applied to the electrode (see figure 5), the Fermi level is lowered and reaches a potential where electrons are transferred from donors in the electrolyte to the metal, and as this occurs, the density of states for the acceptors increases. For example, this process will be observed with a platinum electrode when an anodic current oxidizes the platinum, and since these reaction products remain at the electrode–electrolyte interface, they are available for reduction when a cathodic current is applied. Also encountered on a platinum electrode is electron transfer to protons to create monatomic hydrogen adsorbed to platinum sites during the cathodic phase and desorption transfer of the electron from the adsorbed hydrogen to create protons during the anodic phase.

Figure 6 depicts an electrode–electrolyte system. On the electrolyte side are two donor-acceptor systems, one closely spaced on the energy axis (gray outlines) and the other more widely spaced on the energy axis (black outlines). The double-sided arrow reflects the raising or lowering of the Fermi level by adding or removing electrons, that is, by sweeping the voltage across the interface. As the Fermi level of the metal electrode is raised, the electrode potential becomes more negative (with respect to a reference electrode). Similarly, as the Fermi level is decreased the electrode becomes more positive. When the Fermi level of the metal begins to overlap the donor or acceptor density of states, the probability of electron transfer increases. A measured current can be used to identify the electron transfer reaction. The graph on the left-hand side of figure 6 illustrates a plot of current as a function of overpotential (displacement from a potential where no net current is detected). For the closely spaced density of states (gray outlines), a slight
potential displacement from the zero current potential results in a measured current, and by noticing the current, we learn where a density of states is on a potential basis (gray line). For the widely separated density of states (black outlines), a larger displacement of the overpotential is required to measure a current (i.e., reveal a population of reactants) (black line).

Electron transfer occurs when the reactants are close to the metal surface. Figure 7 represents reactant/reaction-product transport up to and away from the metal interface. For platinum electrodes in the neural stimulation environment, the primary reactants that would be transported to the electrode are oxygen (which can be reduced to form reactive oxygen molecules and or water), water (which can be oxidized to form oxygen and protons and also reduced to form diatomic hydrogen and hydroxyl ions), protons (which can be reduced to form monatomic hydrogen and diatomic hydrogen), charged ions like chloride (Cl \(^{-}\)), and organics (which absorb to platinum and can be oxidized). At a potential of zero current, the concentration of the reactants at the metal interface is generally taken to be the same as the bulk concentration.

**Current flow across the electrode–electrolyte interface as a function of interface potential**

In the preceding sections, we focused on the thermodynamics of electron transfer between the Fermi level and the donor-acceptor state levels and made note that the levels must be equal for radiationless electron transfer. In this section, we want to provide the reader with a sense that not all electron transfer processes are equal by taking into account the kinetics of electron transfer. Mathematically, the idea is expressed as the ‘kinetic facility’ of the redox couple or the ‘standard heterogeneous rate constant’, designated as \( k_0 \), and appears in the Butler–Volmer equation. We provide here an abbreviated version of the derivation of this equation. Consider the electron transfer reaction where a species \( O \) (oxidized) and \( R \) (reduced) are involved in an electron transfer process, equation (1)

\[
O + ne^- \xrightarrow{k_f}{k_b} R.
\]

The flux in the forward direction is the product of the forward rate constant, \( k_f \), and the concentration of the oxidized form, \( C_O \), equation (2)

\[

\nu_f = k_f C_O (x = 0, t) = \frac{i_i}{nFA}.
\]

The flux in the backward direction is the product of the backward rate constant, \( k_b \), and the concentration of the
reduced form $C_R$, equation (3)
\[ \nu_b = k_b C_R (x = 0, t) = \frac{i_0}{nF A}. \] (3)

$n$ is the stoichiometric number of electrons consumed in the electrode reaction.

$C_O$ is the concentration of reduced form of species.

$C_R$ is the concentration of reduced form of species.

$F$ is the Faraday constant.

$A$ is the area.

The net current is given by equation (4):
\[ i = i_c - i_0 = nF \{ k_1 C_O (x = 0, t) - k_b C_R (x = 0, t) \} \] (4)

assuming the rate constants are potential dependent and have a form described by the Arrhenius equation, equation (5):
\[ k = A' \exp(-E_A/RT). \] (5)

where $A'$ is related to the frequency of attempts to surmount an energy barrier $E_A$ and $R$ is the universal gas constant. The net current equation can be reformulated as the current-overpotential equation, a simplified form of it with no concentration ratio coefficients is referred to as the Butler–Volmer equation (6):
\[ i = i_0 \left\{ \frac{C_O (x = 0, t)}{C_O^*} \exp(-\alpha nF \eta) - \frac{C_R (x = 0, t)}{C_R^*} \exp((1-\alpha) nF \eta) \right\} \] (6)

where $i_0 = nF k^0 C_O^0 (1-\alpha) C_R^2 = \text{exchange current}$

$C_O^*$ and $C_R^*$ are bulk concentrations

$f = \frac{F}{RT}$

$k^0$ is the ‘kinetic facility’ of the redox couple or the ‘standard heterogeneous rate constant’

$\eta = E - E_{eq} = \text{overpotential = potential displacement from equilibrium}$

$0 < \alpha < 1 = \text{transfer coefficient = 0.5 for a symmetrical barrier}$
reaction that is less likely to be reversible. The blue line indicates for reorganization of the molecular structure of the reactant and a electron orbitals (equation on platinum. The black line indicates moderate exchange current. The widely separated density of states, smaller exchange current. The widely separated than they are for the case with the larger exchange potential must be increased to a higher value (Point B) before a measurable current can be detected. In the latter case, the separation between the density of states for the donor and acceptor are more widely separated than they are for the case with the larger exchange current. This widely separated density of states, smaller exchange current, signifies electron transfer processes that require more energy for reorganization of the molecular structure of the reactant and a reaction that is less likely to be reversible. The blue line indicates low exchange current (small kinetic facility, requiring significant reorganization of electron orbitals), e.g. diatomic hydrogen formation on platinum. The black line indicates moderate exchange current (moderate kinetic facility, requiring moderate rearrangement of electron orbitals), e.g. oxygen reduction on platinum.

\[ i_0 = nF4k^0C_{O_2}^{1/2}C_{H_2}^{1/2} \]

Figure 8. The current-overpotential equation can give us insight into the behavior of an electrode. For example, if we consider cathodic stimulation (i0, the overpotential is large and negative), then the right-hand side of equation (6) can be ignored. For reactions that have a relatively large exchange current, the measurable current begins at low to moderate values of the overpotential (Point A), illustrated in the figure as \( i_0 = 1 \). For a reaction with a smaller value for the exchange current (\( i_0 = 10^{-4} \) in this example), the overpotential must be increased to a higher value (Point B) before a measurable current can be detected. In the latter case, the separation between the density of states for the donor and acceptor are more widely separated than they are for the case with the larger exchange current. The widely separated density of states, smaller exchange current, signifies electron transfer processes that require more energy for reorganization of the molecular structure of the reactant and a reaction that is less likely to be reversible. The blue line indicates low exchange current (small kinetic facility, requiring significant reorganization of electron orbitals), e.g. diatomic hydrogen formation on platinum. The black line indicates moderate exchange current (moderate kinetic facility, requiring moderate rearrangement of electron orbitals), e.g. oxygen reduction on platinum.

\[ k^0 \] has values that range between 10 and \( 10^{-9} \), larger values for simple electron transfer processes, and smaller values for sluggish reactions that require molecular rearrangement, such as equation (7):

\[ \text{H}^+ + e^- \rightarrow \text{H}, \quad 2\text{H}^+ + \text{O}_2 + 2e^- \rightarrow \text{H}_2\text{O}_2 \]

(7)

Sluggish reactions require a greater overpotential

When the overpotential \( \eta = E - E_{eq} \) is large and negative, the first term on the right-hand side of equation (6), dealing with electron transfer to the oxidized form of the species, dominates the equation and the term dealing with the reduced form of the species can be ignored. This reasoning will also apply to the case when \( \eta \) is large and positive: the second term on the right-hand side of equation (6) dominates, and the term dealing with the oxidized form of the species can be ignored.

In figure 8 is shown a graph of cathodic current resulting from a decreasing overpotential, \( \eta \). Two curves are depicted: \( k^0 \) the kinetic facility of the electron transfer is small, which means \( i_0 \) is small (\( i_0 = 10^{-4} \), blue curve), and an example for a somewhat larger \( k^0 \) (\( i_0 = 1 \), black curve). From this behavior we see that when the kinetic facility of electron transfer is sluggish, the probability of an electron transfer becomes appreciable (measureable current) only at larger overpotentials.

Now consider cases where the reactant, \( C_{O_2}(x = 0) \), becomes depleted in the course of sweeping the potential of the electrode–electrolyte interface.

Case (1). The reactant is confined to the surface of the platinum electrode, e.g. platinum oxide and the bulk concentration of the reactant is zero. Referring to figure 9, as the interface overpotential, starting at \( \eta = 0 \), is made more negative by injecting negative charge, the measured current starts to follow the \( \eta = 1 \) pathway at Point A (gray dotted line). When the potential reaches a value designated by Point C, the availability of the reactant \( C_{O_2}(x = 0) \) cannot be supplied at the rate following the Butler–Volmer equation, and the current decreases to zero. As \( C_{O_2} \) becomes zero, the oxide becomes completely depleted. If the interface potential continues to increase, \( \eta \) reaches a potential where electron transfer becomes favorable to the reactant characterized by \( i_0 = 10^{-4} \) at Point B. If the concentration of the second reactant is not challenged by mass transport, the measured current increases rapidly with increasing \( \eta \), following Butler–Volmer.

When reactants become limited (platinum oxide and dissolved oxygen)

Figure 9. Electron transfer processes for an electrode immersed in an electrolyte that contains two potential reactants, one described by an exchange current like that shown for \( i_0 = 1 \) and the other having an exchange current like that shown for \( i_0 = 10^{-4} \). The reactant for \( i_0 = 1 \) has a fixed amount and is an intimate part of the surface and not found in the electrolyte. The top graph represents the depletion of the oxidized surface-bound reactant for \( i_0 = 1 \) as the overpotential is moved negative of Point A. An example of this type of reaction is the reduction of platinum oxide. When the interface potential is under voltage control and is swept past Point C, the electron transfer reaction cannot follow the requirements of the \( i_0 = 1 \) curve and the current decreases because the reactant is depleting. If the sweep rate is slow enough, the reactant can be completely depleted before the interface potential become sufficient to drive the \( i_0 = 10^{-4} \) reaction, e.g. a current–voltage pathway illustrated by the dotted line.
Figure 10. Electron transfer processes for an electrode immersed in an electrolyte that contains two potential reactants, one described by an exchange current like that shown for $i_0 = 1$ and the other having an exchange current like that shown for $i_0 = 10^{-4}$. The reactant for $i_0 = 1$ is found in the electrolyte with a bulk concentration of $C_0^*$. This illustration is representative of the reduction of dissolved oxygen where electron transfer to a reactant becomes limited by the rate the reactant can be transported to the electrode interface (i.e., diffusion limited, mass transport limited). When the interface potential is under voltage control and is swept past Point C, $C_0(x = 0)$ becomes zero and the reaction becomes limited by the rate at which the reactant can be supplied from the bulk to $x = 0$. The current (i.e. proportional to the reaction rate) is described by $i = nFAm_0C_0^*$. This equation uses a linear approximation for the concentration gradient at $x = 0$. As the overpotential becomes more negative and moves past Point B, the reactant for $i_0 = 10^{-4}$ can be reduced simultaneously with the reactant for $i_0 = 1$, and the currents for both reactions sum. If a cathodic current pulse is applied to the electrode, charge is added to the electrode for the duration of the pulse; the potential across the electrode/electrolyte interface becomes more negative as the double layer capacitance charges. The Fermi level for the electrons in the metal begins to increase, but no significant current flows until the overpotential becomes more negative than Point A. As current begins to flow, the first reactant is reduced and the concentration at the electrode/electrolyte interface ($C_0(x = 0)$) begins to diminish. It is entirely possible that the rate at which current is injected into the electrode does not permit sufficient time for transport of the reactant and only the reactants present at $x = 0$ are reduced and the interface potential moves to a value where $i_0 = 10^{-4}$ is favored. Even though the interface potential may be well negative of Point A, as the reactant is transported to the electrode, the electron transfer will still occur.

**Case (2).** The reactant is diffusion limited, e.g. dissolved oxygen at $C_0^*(x = 0)$ is reduced at a rate faster than dissolved oxygen can be brought to the electrode for electron transfer.

Referring to figure 10, as the overpotential, $\eta$, is swept negatively from zero, the measured current (gray dotted line) follows the black line for $i_0 = 1$ until Point C. During this time the concentration $C_0(x = 0)$ is decreasing from $C_0^*$ to zero at which point, Point C, the measured current is mass transport limited and is given by:

$$i = nFAm_0C_0^*$$

where $m_0$ is the ratio of the diffusion coefficient to the diffusion layer thickness. Increasing the overpotential beyond Point C does not produce an increase in measured current until Point B, a potential where the reaction described by $i_0 = 10^{-4}$ becomes possible. At potentials more negative than Point B, the reaction designated by $i_0 = 10^{-4}$ becomes favorable and the current follows the blue line as $\eta$ is made more negative. This could be the case when the electrolyte in which the platinum electrode is operating contains dissolved oxygen, and the rate at which charge is injected drives the overpotential into a region where reaction $i_0 = 10^{-4}$ is favored, e.g. formation of diatomic hydrogen.
We have learned that as charge is injected into a metal electrode immersed in an electrolyte, the energy of the electrons in the metal increases for negative charge injection and decreases for positive charge injection. We have also learned that an electron can only be transferred between the metal electrode and the electrolyte when the Fermi level for the electrons in the metal align with the electron energy level of an acceptor or donor state in the electrolyte. Insight into the position of the donor and acceptor sites on the interface voltage axis can be determined by measuring the current flowing as a function of the interface potential. For example, when the Fermi level and a donor or acceptor site are matched, current flows and can be measured. In figure 11 we show a cartoon representation of a measurement system used to identify the donor and acceptor sites. This measurement system is referred to as a three-electrode system, which includes the working electrode, the counter electrode, and the reference electrode. The potential across the reference electrode interface does not change because (1) to qualify as a reference electrode, very little change in the interface potential occurs with small current flow, and (2) little or no current flows through the reference electrode because measurements are made with a very high input impedance device ($\sim 10^{13}\, \Omega$). If the interface potential was measured between the working electrode and the counter electrode, two changing interface potentials would be measured at the working electrode interface and the counter electrode interface.

The electrode of interest is the working electrode, which in this treatment will be platinum. Current is driven through the working electrode and counter electrode to force the potential between the reference electrode and the working electrode to be a predetermined value. For this discussion the potential will be a linear function of time with successive positive and negative gradients, producing a sawtooth waveform. The counter electrode is usually constructed in a manner that reactions occurring on it do not contaminate the electrolyte, e.g. it is physically removed and electrically connected by a salt bridge, very large so that the potential does not exceed the double layer charging area, or the electrode is inert in the range of testing. The potentiostat is designed to drive a current through the working electrode and
counter electrode such that
\[ \frac{dV}{dt} = K, \]
where \( K \), the sweep rate, is a constant and slow enough (in the range of 10–100 mV s\(^{-1}\)) to consider the electrode interface to be in a state of equilibrium, meaning the measurement provides the user with thermodynamic information, or steady-state information, not kinetic information, which will come into play during rapid changes in the interface potential.

Figure 12 shows a cartoon representation of \( V_e(t) \) and \( i(t) \) as might be seen from a recording made with an oscilloscope (lower panel of figure 12). Plotting \( i(V_e) \) yields the \( i(V_e) \) profile also known as the CV (upper panel of figure 12 [6]).

**Information to be gleaned from the platinum \( i(V_e) \)**

We want to prepare the reader to extract meaning from the \( i(V_e) \) profile. First, consider the \( i(V_e) \) profile for two electrical circuit elements, a resistor and a capacitor (see figure 13).

Charge moving through a resistor element is energy lost, and charge moved onto a capacitor is charge stored and recoverable. The left-hand panel of figure 13 shows a resistor (\( R \)) and the \( i(V_e) \) profile (aka CV) for the resistor, a line with a slope of \( 1/R \). The right-hand panel shows a capacitor (\( C \)), and the \( i(V_e) \) profile for the charge storage element. The energy dissipation element is an electric analog for an unrecoverable electron transfer reaction, aka unrecoverable faradaic reaction. The charge storage (capacitor) element is an electrical analog for either double-layer charging or a recoverable electron transfer reaction, i.e. the reaction product is close enough to the metal interface that an electron can be exchanged between the electrode and the reactant when the potential becomes favorable, aka recoverable faradaic reaction. Equal areas above and below the \( i = 0 \) line are the signature for reversible electrochemical reactions, and, generally speaking, are desirable from a neural stimulation perspective. An example of such reversible reactions for a platinum electrode is hydrogen atom adsorption (see figure 14).

Keep in mind that we only have hydrogen desorption as a reactant if we have deposited atomic hydrogen during a cathodic sweep or pulse. Similarly, we have only platinum oxide as a reactant when we have created that oxide on the positive sweep or anodic pulse. Referring back to figure 12, notice that in terminating the positive sweep at ‘1’, no oxide is reduced on the negative sweep cycle because the positive sweep was terminated before the potential was favorable for oxide formation. Using a linear sweep to create the \( i(V_e) \) makes it easy to calculate how much charge could be injected as a reversible process when operating in a particular region the of \( i(V_e) \) profile, say between \( V_{e1} \) and \( V_{e2} \).

\[
\frac{\Delta Q}{\Delta V} = \int_{V_{e1}}^{V_{e2}} \frac{i(V_e)}{A} \, dt
\]
This area has a theoretical charge-storage capacity of \(2 \times 10^9\) \(\mu C\) cm\(^{-2}\), approximately equal. On the left-hand side, atomic hydrogen is adsorbed to the platinum surface. Several important features of the profile are indicated. The blue shaded area above the zero current line and the area below the zero current line are approximately equal. On the left-hand side, atomic hydrogen is adsorbed to the platinum surface (green shaded area) as the potential is moved in the negative direction. This area has a theoretical charge-storage capacity of \(210 \mu C\) cm\(^{-2}\) [9, 10]. As the potential is moved in the positive direction, the atomic hydrogen is desorbed from the surface (left side of the blue shaded area above). On the right-hand side of the blue area, platinum is oxidized (platinum oxides are formed), and it is reduced in the unshaded region below the zero-current line. The region in the center of the profile, labeled double layer charging, is where the current is approximately constant and no electron transfer processes occur. This process is also known as charging the double layer capacitance, and occurs across the entire potential range, simultaneously with all other processes. At interface potentials at the extreme left, diatomic hydrogen is formed (generally considered irreversible). At interface potentials at the extreme right, diatomic oxygen is formed, and it is also generally considered to be an irreversible reaction. Between the two extremes is generally referred to as the ‘water window’ in the neural prosthesis community. This figure was redrawn from Angerstein-Kozlowska et al. (1973).

since \(K = \frac{dV}{dt}\)

\[
\frac{Q}{A} = \int_{V_1}^{V_2} \frac{i(V)}{A} \left(\frac{1}{K}\right) dV. \tag{11}
\]

Other features of the \(i(V_e)\) profile noted in figure 14 are:

- The \(i(V_e)\) curve is bounded by a voltage region of rapidly increasing current, oxygen evolution (O\(_2\)) on the far right side, and a voltage region of rapidly increasing current in the negative direction, hydrogen evolution (H\(_2\)) on the far left side. This bounded region is denoted as the ‘water window’. Oxygen evolution and hydrogen evolution are accepted to be irreversible processes. (Although not the usual case, these reactions may be reversed if the reaction products have not diffused too far from the surface before the reversal pulse is applied.)
- In the center region of the \(i(V_e)\) profile is an area where the current is more or less constant, denoted as the double-layer charging region. It should be noted that double layer charging takes place over the entire range of the voltage sweep. Referring back to figure 6, the Fermi level is moving through a potential region where there are neither donor nor acceptor states available. The current in this region is:

\[
i(V_e) = C_{dl} \frac{dV_e}{dt} = C_{dl} K, \tag{12}
\]

where \(C_{dl}\) is the double-layer capacitance, ~20 \(\mu \)F cm\(^{-2}\) for platinum and \(K\) is the sweep rate when the \(i(V_e)\) was recorded.

**Concluding remarks by JTM**

Platinum or platinum iridium alloys are the most used electrode materials for electrical excitation of the nervous system. Many of us were drawn to platinum, believing it was inert, a belief that turned out to be not quite true as Rosenberg [7] discovered. Barry Brummer, through the Neural Prosthesis Program at the NIH, brought some of us (JTM) to consider the electrochemistry of stimulating electrodes; he pointed out the reversible electron transfer processes platinum exhibited, implying that if stimulation was confined to the ‘water window’, one could expect to inject more than \(210 \mu C\) cm\(^{-2}\) in the cathodic pulse without generating products that could be toxic to cells in the vicinity of the stimulating electrode. Experimental data do not agree with this number, and the upper limit is more like \(30 \mu C\) cm\(^{-2}\) for safe stimulation with...
Figure A1. Electrical circuit representation of electrochemical cell connected to a potentiostat. The data reported in figure 14 were acquired with the measurement technique shown here. The potentiostat is a commercially available device that is programed to produce a saw tooth voltage waveform, see figure 12, between the working electrode, which we ground, and the reference electrode. The output of the potentiostat is the voltage between the reference electrode and the working electrode, and the current flowing through the working electrode, \( i \). The circuit representation of the electrochemical cell contains a working electrode, which is the electrode of interest, the reference electrode, and the counter electrode, which is required for current return. The electron transfer processes occurring at the working electrode interface are characterized by a parallel combination of the double layer capacitance, \( C_{we} \) and electron transfer processes described by the Butler–Volmer equation. \( R_{etp1}, R_{etp2}, \ldots, R_{etp} \) have been lumped into a single voltage-dependent resistor, \( R_{we} \). The counter electrode would be governed by a similar representation, but has been removed from the measurement by the use of a reference electrode. \( R_{sol} \) and \( R_{\Omega} \) are representations required for a potential drop in the electrolyte medium.

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Appendix. Electrical circuit representation of electrochemical cell

Our goal is to make it easy for folks in the neuroprostheses community to incorporate the electron transfer processes into their thinking as they design and work with neurostimulating devices. To that end, we find that an electrical circuit representation of figure 14, shown in figure A1, can serve a good purpose.

Focus first in the box labeled ‘working electrode’, the part of the system we are most interested in. Within this box are two elements, \( C_{\text{we}} \) and \( R_{\text{we}} \). These two elements represent all of the concepts presented in figures 2–5, 8–10, 12, and, most importantly, 14. \( C_{\text{we}} \) represents the double layer capacitance; charge accumulating at the metal–electrolyte interface, electrons on the metal side and ions on the electrolyte side. \( R_{\text{we}} \) represents a parallel combination of unrecoverable electron transfer processes, \( R_{\text{etp1}} \), \( R_{\text{etp2}} \), \ldots, \( R_{\text{etpn}} \). The current through these elements follows the Butler–Volmer equation, each with its own \( \eta_0 \) and \( C_O \) or \( C_R \):

\[
i = i_0 \left\{ \frac{C_O}{C_R^*} \exp(-\alpha n \eta j) - \frac{C_R}{C_R^*} \exp((1 - \alpha) n \eta j) \right\}
\]  

(13)

For example, let us assume the current is moving in the direction shown for ‘\( i \)’, meaning the potential across the working electrode is moving in the negative direction. Also, assume that the beginning \( V_{\text{we}} \) was somewhere in the double layer region, figure 14, which is reasonable to assume. As \( V_{\text{we}} \) becomes more negative, charge is accumulating on \( C_{\text{we}} \) until a potential is reached for electron transfer to occur into the diatomic hydrogen adsorption reaction. We could say that \( R_{\text{etp1}} \) represents the hydrogen adsorption electron transfer process, forming \( C_O \). If the potential were made more negative yet, electron transfer could be energetically favorable for diatomic hydrogen formation, say current flowing through \( R_{\text{etp2}} \), which will likely diffuse away from the interface. Now consider moving \( V_{\text{we}} \) in the opposite direction, \( V_{\text{we}} \) becoming positive, when the interface potential becomes sufficient, electron transfer can result in platinum oxide formation. This reaction results in a reaction product, \( R_{\text{pt}} \), that becomes available when the electrode later moves negatively and into a region where oxide reduction becomes favorable, \( R_{\text{pt}} \). Take note: \( C_{\text{we}} \) is in parallel with the interface representation and is always at the same potential as that for reactions \( R_{\text{etp}} \). This means that if the potential across \( C_{\text{we}} \) is sufficient to drive \( R_{\text{etp}} \), that reaction will proceed until \( V_{\text{we}} \) drops to a value where it is unlikely to occur.

The importance of the potential across \( C_{\text{we}} \) becomes apparent when regulated pulses are applied to the working electrode. Referring to figure 10, let \( \eta_0 = 1 \) represent oxygen reduction and \( \eta_0 = 10^{-4} \) represent diatomic hydrogen formation. A current pulse could drive \( V_{\text{we}} \) negative into a region where diatomic hydrogen forms. At the termination of the current pulse the potential across \( C_{\text{we}} \) is sufficient to drive the reaction \( \eta_0 = 1 \) until the potential across \( C_{\text{we}} \) discharges to a value where oxygen can no longer be reduced, even though it is present. This means that the reaction described by \( \eta_0 = 1 \) continues after the current pulse is terminated!

Returning to figure A1, as a whole, two components are shown in this figure: the circuit representation of the electrochemical cell and the potentiostat. The potentiostat is programmed to force the potential between the working electrode and the reference electrode to produce the saw tooth waveform shown in figure 12, starting and ending potentials can be set as well as the sweep rate. The current flowing in the system is recorded and reported as an output along with the corresponding voltage.

The circuit representation for the electrochemical cell is also used for pulsing experiments in subsequent communications. When the pulsing experiments were performed the working electrode was connected to building ground and that is the electrical configuration used with the potentiostat measurements.

A three electrode measurement system was employed, which is comprised of the working electrode (the electrode of interest), the reference electrode (an Ag/AgCl electrode in our case), and a counter electrode to accommodate the return of the current passed through the working electrode. The reference electrode makes it possible to isolate the working electrode potential from the counter electrode potential changes during current passage. The current flowing through the working electrode is \( i \), which is the same as that reported by the potentiostat. The working electrode is in an electrolyte and the reference and counter electrode are in the same ionic medium. Current flow in the working electrode and counter electrode is supported by electron migration in the metals. In the electrolyte ion migration supports the current. When current is flowing between the counter electrode and the working electrode a voltage drop will occur in the ionic medium, represented in the figure as \( V_{\text{fl}} \). The voltage measured between the ground point and the reference electrode is:

\[
V_{\text{fl}} = V_{\Omega} + V_{\text{we}}.
\]  

(14)
For $V_{re}$ to be an accurate reflection of $V_{we}$, $V_{i}$ must be compensated for or negligible. Generally speaking, $i$ is small for potentiostat measurements and so $V_{i}$ can be neglected. During pulsing experiments $V_{i} = iR_{i}$ cannot be neglected. Therefore

$$V_{we} = V_{re} \sim iR_{i}.$$  \hspace{1cm} (15)

This calculation requires an estimate of $R_{i}$, which will be covered in a companion communication. For this discussion, $V_{i}$ is treated as negligible.

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