# Using Cyclic Voltammetry and Molecular Modeling To Determine Substituent Effects in the One-Electron Reduction of Benzoquinones

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New electrochemical instrumentation, based on sensitive computer-controlled potentiostats and a variety of new stationary electrodes and microelectrodes, provides a host of powerful voltammetric and coulometric methods for fundamental studies of electrochemical reactions. Cyclic voltammetry (CV), one of the most versatile of these new techniques, is often the first experiment performed in an electrochemical study and is used extensively in organic chemistry, biochemistry, and inorganic chemistry (*1*). Several articles have appeared in this *Journal* addressing the theory and importance of CV in the undergraduate curriculum (*2–11*).

A knowledge of substituent electronic effects is essential to the understanding of relative rates, equilibrium constants, and reactive intermediates of both in vivo and in vitro reactions. Several important relationships between substituents and chemical properties, including redox behavior, have been developed. The most widely applied of these relationships is the Hammett equation (*12*). At Lebanon Valley College, we have developed an electrochemical experiment using substituted benzoquinones, which combines electrochemistry, molecular modeling, and the Hammett equation. This experiment can be used in either an organic, physical, or instrumental laboratory course.

## Rationale and Theory

Quinones are a class of compounds that have widespread importance in biology and chemistry. Quinones, for example, function in cellular respiration, photosynthesis, and blood coagulation. Their biological action is often linked to their electron transfer rates and redox potentials (*13*).

Quinone/hydroquinone redox couples have been widely used in electrochemical studies because they are readily available and exhibit "well behaved" electrochemistry. In aprotic solvents, quinones are reduced in two successive one-electron steps to form the radical anion ($Q^{\cdot-}$) and hydroquinone dianion ($Q^{2-}$) (*14*). A cyclic voltammogram showing the two successive electron transfer steps for the substrate tetrachloro-1,4-benzoquinone dissolved in acetonitrile is given in Figure 1. In this figure, the scan from +0.7 V to −1.0 V is the cathodic wave, causing the reduction of the quinone. At the vertex potential of −1.0 V, the scan is reversed to provide the oxidative anodic wave. Formal reduction potentials ($E^{o\prime}$) for each step can be determined from the anodic ($E^a$) and cathodic ($E^c$) peak potentials for the $E^1$ and $E^2$ steps, shown in Figure 1, using equation 1 (*15*):

$$E_1^{o\prime} = \frac{E_1^a + E_1^c}{2} \quad \text{and} \quad E_2^{o\prime} = \frac{E_2^a + E_2^c}{2} \tag{1}$$

For substituted quinones, the value of the reduction potential depends on the electronic properties of the substituents. Electron-withdrawing groups make reduction potentials more positive by stabilizing the $Q^{\cdot-}$ and $Q^{2-}$ reduction products, while electron-donating substituents have the opposite effect. For quinone systems, cyclic voltammograms for the $E_1$ step are known to be more reversible and reproducible than those for the $E_2$ step (*16*). For this reason, we use only measurements for the $E_1$ reduction step in this experiment.

The Hammett equation has been used to assess the electronic effects of a substituent R attached directly to an aryl system upon a reaction center meta or para to R. Although originally based on dissociation constants of substituted benzoic acids, the Hammett equation is applicable to a variety of equilibria of substituted aromatic compounds (*17*). The Hammett equation is shown in eq 2, where $K$ is the equilibrim constant of a reaction involving a substituted aryl system and $K_0$ is the equilibrium constant for the unsubstituted parent compound.

$$\log K - \log K_0 = \log \frac{K}{K_0} = \sigma\rho \tag{2}$$

The Hammett substituent constant, σ, is characteristic of the electronic effect of a substituent. Electron-withdrawing substituents have positive σ values and electron-donating groups have negative values. The magnitude of σ also varies according to its position on the aryl ring relative to the reactive site. The reaction constant ρ is characteristic of the sensitivity of the reaction to substituent electronic effects. A positive value of ρ indicates that the reaction is enhanced by electron-withdrawing groups, whereas a negative value denotes enhancement by electron-donating groups. The magnitude of ρ indicates whether the reaction is more or less sensitive to substituent electronic effects than benzoic acid dissociation.

The equilibrium constant of a reaction can be expressed in terms of its standard electrochemical potential ($E^\circ$), as given by equation 3,

$$\log K = \frac{n\mathcal{F}E^\circ}{2.303\,R\,T} \tag{3}$$

where $n$ is the number of moles of electrons transferred, $\mathcal{F}$ is the Faraday constant, $R$ is the universal gas constant, and $T$ is the absolute temperature (*18*). Combining eqs 2 and 3 gives eq 4,

$$\log K - \log K_0 = \frac{n\mathcal{F}E^\circ}{2.303\,R\,T} - \frac{n\mathcal{F}E_0^0}{2.303\,R\,T} \tag{4a}$$

or

$$\log \frac{K}{K_0} = \frac{n\mathcal{F}}{2.303\,R\,T}\Delta E^\circ = \sigma\rho \tag{4b}$$

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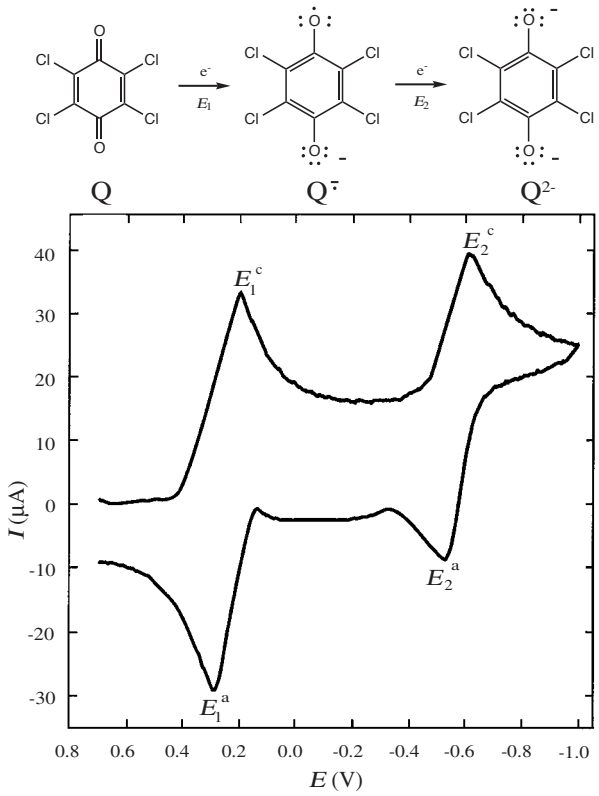


Figure 1. Cyclic voltammogram for tetrachloro-1,4-benzoquinone in acetonitrile.

where $E°$ and $E_0°$ are the standard potentials of the substituted and parent compounds, respectively. The substituted benzoquinones used in this experiment often contain multiple substituents, the cumulative effect of which can be expressed as $\Sigma\sigma$, the sum of the $\sigma$ values for each substituent (*19–21*). In addition, we assume in this experiment that the formal reduction potentials ($E°'$) we measure by CV are good approximations of the standard state reduction potentials ($E°$). Thus, for a one-electron electrochemical reduction reaction at 25 °C, such as the $E_1$ step in Figure 1, equation 4 can be written as

$$E°' - E_0°' = \Delta E°' = [0.0592\rho]\Sigma\sigma \qquad (5)$$

Equation 5 predicts that a Hammett plot of $\Delta E°'$ versus $\Sigma\sigma$ will be linear. The reaction constant, $\rho$, can be determined directly from the slope of the plot.

## Experimental Procedure

### Electrochemistry

A list of commercially available benzoquinones (Aldrich) appropriate for this experiment is shown in Table 1. Anhydrous solvents, acetonitrile or *N,N*-dimethylformamide (DMF), are available from Aldrich. The supporting electrolyte, tetrabutylammonium perchlorate, is available from Sigma.

Cyclic voltammetry was carried out using a Model 273A potentiostat/galvanostat from EG&G Princeton Applied Research. The gold working electrode (model G0277), platinum counter electrode (model K0266), and silver/silver chloride reference electrode (model K0265) were obtained from EG&G PAR. Cyclic voltammetry measurements were carried out in a thermostated microcell at 25.0 °C in the desired aprotic solvent containing 0.10 M tetrabutylammonium perchlorate as supporting electrolyte and 2.0 mM quinone substrate. All samples were purged with nitrogen with stirring for 2 min to remove oxygen before voltammetric measurements. The voltammetric parameters were as follows: initial potential was 0.80 V; vertex potential was –1.80 V; and the scan rate was 50 mV/s. The potential range listed accommodates all quinones in Table 1 and can be shortened in most cases to expedite the experiment.

### Molecular Modeling (Optional)

CAChe version 3.8 (MOPAC version 94.10 using the AM1 Hamiltonian [*22*]) was used to calculate quinone LUMO energies.

## Results and Discussion

Students obtain CV data, using anhydrous acetonitrile or DMF containing tetrabutylammonium perchlorate as a supporting electrolyte, for benzoquinone plus a minimum of four substituted benzoquinones. The first reduction potential ($E_1$) for each quinone is determined using eq 1. Using $E_1$ data, students calculate $\Delta E_1°'$ for the quinone series by subtracting the measured reduction potential of the parent benzoquinone from the potential of the substituted quinone. Using reported $\sigma$ values (*12*) for the substituents, students plot $\Delta E_1°'$ versus $\Sigma\sigma$. Previous reports indicate that $\sigma_p$ values give the best correlation for all substituents with the exception of chlorine, whose inductive effect is more accurately reflected by $\sigma_m$ for quinone systems (*16*). The value of $\rho$ is determined by dividing the slope of the plot by 0.05915. A typical plot of student data using *N,N*-dimethylformamide (DMF) as a solvent is shown in Figure 2. The value of $\rho$ in DMF is 6.37 with a correlation coefficient ($R^2$) of .99. Acetonitrile also gives a good correlation ($\rho$ = 6.68, $R^2$ = .99) (*16*).

**Table 1. Electrochemical and Hammett Data for 1,4-Quinones**

| Quinone | $E°'$ | $\Delta E°'$ | $\Sigma\sigma$ |
|---|---|---|---|
| 1,4-Benzoquinone | -0.2586 | 0.0000 | 0.00 |
| 2,3-Dichloro-5,6-dicyano-1,4-benzoquinone | 0.7121 | 0.9707 | 2.74 |
| 2,6-Dimethyl-1,4-benzoquinone | -0.4282 | -0.1696 | -0.34 |
| 2-Chloro-1,4-benzoquinone | -0.0885 | 0.1701 | 0.37 |
| 2-Methyl-1,4-benzoquinone | -0.3430 | -0.0844 | -0.17 |
| 2-Phenyl-1,4-benzoquinone | -0.2545 | 0.0041 | 0.05 |
| Tetrachloro-1,4-benzoquinone | 0.2572 | 0.5158 | 1.48 |
| Tetramethyl-1,4-benzoquinone | -0.5909 | -0.3323 | -0.68 |

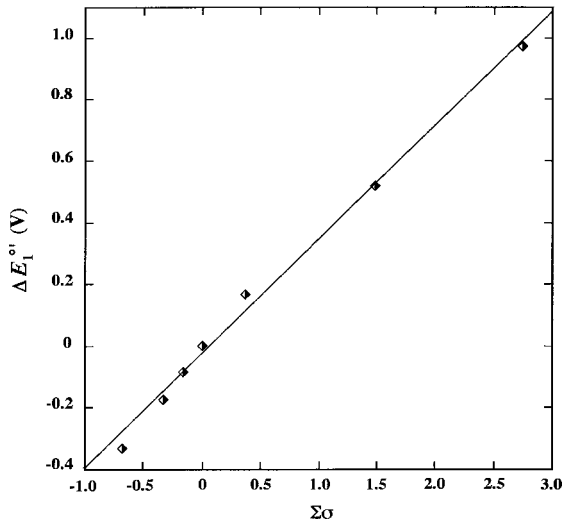


Figure 2. Hammett plot of quinone $\Delta E_1^{o\prime}$ versus Σσ.

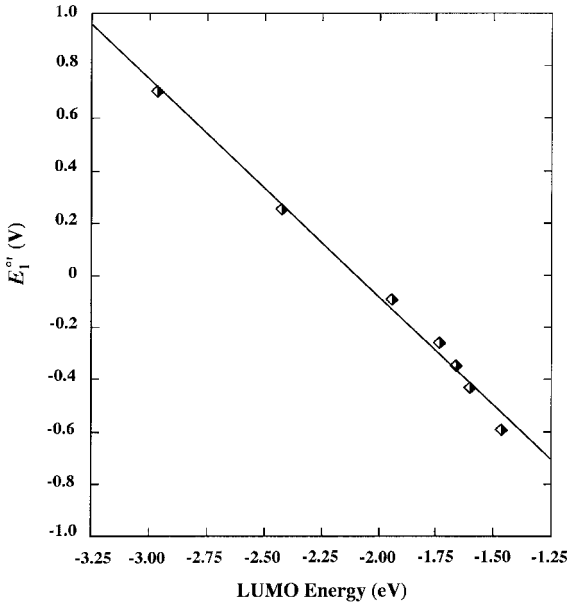


Figure 3. Plot of $E_1^{o\prime}$ versus calculated LUMO energy.

A valuable addition to this laboratory experiment combines molecular modeling with electrochemistry. We ask our students to use the semi-empirical AM1 method (MOPAC) to calculate the energy of the lowest unoccupied molecular orbital (LUMO) of each quinone that they used to determine their Hammett plots. They then plot the measured reduction potentials ($E_1$) of the substituted benzoquinones versus their LUMO energies, as shown in Figure 3. Students are asked to explain the strong correlation ($R^2$ = .99) between reduction potential and LUMO energy. We want them to discover that the incoming negative electron in the reduction process will add most favorably (i.e., its associated reduction potential will be the most positive) to the quinones in the series having the most stable (lowest energy) LUMOs. This experiment clearly demonstrates to students how substituent electronic effects affect the energies of molecular orbitals in aryl systems.

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