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Glassy carbon electrodes deliver unpredictable reduction potentials for platinum(IV) antitumor prodrugs

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This paper is dedicated to Professor Malcolm Chisholm on the occasion of his 70th birthday and in celebration of his many contributions to organometallic chemistry.

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ABSTRACT

Reductive activation of six-coordinate Pt(IV) complexes to afford square-planar Pt(II) complexes has exhibited surprisingly divergent and unpredictable cathodic peak potentials during cyclic voltammetry (CV) measurements under widely employed experimental conditions. A systematic, detailed investigation reveals that glassy carbon (GC) electrodes are responsible for this erratic behavior. More reproducible CVs are obtained with platinum metal electrodes, which display cathodic responses at much more positive potentials. The unreliable and negatively shifted peak potentials observed at GC are attributed to a non-uniform oxide layer that is formed on the electrode surface causing slow electron transfer. A simple procedure of repetitive scanning to reducing potentials is found to be effective for cleaning and activating the GC surface, such that it exhibits the more consistent and accurate peak potential responses seen with a Pt electrode.

1. Introduction

Cyclic voltammetry (CV) often is the method of choice for investigating the electrochemical properties of inorganic complexes. As such, it is important to establish that the measured voltammetric parameters correlate accurately with the chemical properties of interest. A common practice for obtaining the standard redox potential, $E°$, is to average the cathodic and anodic peak potentials, E_{pc} and E_{pa}. However, if the electrode reaction is irreversible by virtue of either slow electron-transfer kinetics or a coupled chemical reaction, such as electrochemically triggered bond cleavage, only the cathodic peak potential may be observed during the course of a reduction [1]. In these irreversible cases, the common protocol of averaging E_{pc} and E_{pa} cannot be applied. Moreover, the irreversible peak potential may shift to either positive or negative values with its position and shape varying as a function of scan rate, making it difficult to obtain an accurate estimate of the true $E°$. Another serious and often unappreciated problem is that redox reactions become non-Nernstian when chemical events like ligand loss disturb the equilibrium connecting the oxidized and reduced forms. Typically, the concentration of the free ligand in the electrolyte solution is negligibly small, which makes it impossible to establish a chemical equilibrium between the reactant and product states. Because the Nernst equation assumes that oxidants and reductants are in thermodynamically well-defined equilibrium, chemically irreversible redox reactions are non-Nernstian by default, adding significantly to the difficulty of interpreting the electrochemical responses of these complicated, but relatively common processes.

Recently [2], we studied the electrochemical reduction of several six-coordinate Pt(IV) complexes that are representative examples of third generation antitumor prodrugs [3–23]. These compounds undergo two-electron reduction accompanied by loss of two axial ligands to afford a square-planar Pt(II) complex (Scheme 1). The resulting voltammetric responses are irreversible. However, by analyzing scan rate-dependent changes in the position and shape of the Faradaic response using a protocol introduced by Jean-Michel Savéant and others [24–35] we have been able to determine the (stepwise) mechanism of this two-electron process and to extract the standard potential, $E_{1,s}°$, of the initial one-electron addition to Pt(IV).

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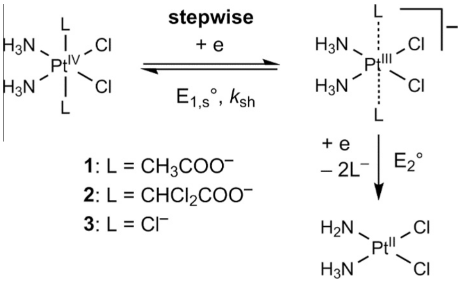

Scheme 1. Two-electron reduction with subsequent ligand loss follows a stepwise mechanism for compounds **1–3** as determined in Ref. [2].

Investigations seeking to establish relationships between structure and activity of these clinically important compounds need to be based on an accurate and reliable determination of a relevant fundamental parameter, in this case the standard reduction potential $E°$. Because of the irreversibility of the electrode reaction, many researchers have chosen to use the cathodic peak potential, E_{pc}, as a substitute for $E°$ in evaluating the efficacy of Pt(IV) prodrugs [6,15,16,18–20,23]. E_{pc} is a valid approximation of $E°$ only in the case of nearly ideal, reversible redox reactions, where the separation between E_{pc} and E_{pa} is ca. 60/n mV and E_{pc} is more negative than $E°$ by only ca. 30/n mV [1]. In assessing the relative ease of reduction of various Pt(IV) prodrugs, researchers have reported E_{pc} values measured under comparable, yet arbitrarily established, experimental conditions. The underlying assumption is that potential differences between E_{pc} and $E°$ are identical in all circumstances and cancel to generate a qualitatively meaningful correlation. However, the complicated mechanistic and thermodynamic issues discussed above raise serious concerns about the validity of such a simplified approximation, as highlighted in our recent study [2].

During the course of our work we found that linear sweep and cyclic voltammograms of selected Pt(IV) prodrugs showed irreproducible peak potentials that varied greatly with experimental conditions and produced estimates of $E°$ that were grossly inconsistent with quantum chemically calculated values. Subsequently, we have identified glassy carbon (GC) electrodes to be the source of these inconsistencies and have examined the voltammetric response of Pt(IV) systems in greater detail at GC and Pt electrodes to better understand the extent and nature of the artifactual shifts in peak potential. The goal of this work is to identify the source of the erratic behavior and to provide a basis for interpreting previous work obtained at GC electrodes in a conceptually more satisfying manner. In addition, we report a simple experimental procedure that allows more consistent and reliable data to be obtained at glassy carbon electrodes.

2. Experimental

2.1. Synthesis of complexes

Platinum prodrugs **1**–**3** were generously provided by Professor Stephen J. Lippard (Massachusetts Institute of Technology, Cambridge, MA). The general procedures for the synthesis of these prodrugs have been reported previously elsewhere [13,20].

2.2. Electrochemistry

Cyclic voltammetry experiments of all Pt(IV) prodrugs were conducted in a three-electrode cell and recorded at room temperature with an EG&G PAR 273A or a CH Instruments 620E potentiostat. The working electrode was a platinum disk (Bioanalytical Systems, area = 0.02 cm^2) or a glassy carbon disk (Bioanalytical Systems, area = 0.07 cm^2), the reference electrode was Ag/AgCl (Bioanalytical Systems, satd. NaCl) and the counter electrode was a platinum wire. The potential of the Ag/AgCl electrode is +0.197 V vs. SHE. Pt(IV) complexes were dissolved in water to prepare 1 mM solutions with 0.1 M sodium acetate (for **1**) or potassium chloride (for **2** and **3**) as the supporting electrolyte. Solutions were degassed with Ar for 5–10 min before experimentation, and each voltammogram was collected under a blanket of Ar. The Pt and GC electrodes were polished for at least 2 min between trials with 0.05-μm γ-alumina (Buehler) slurry on a polishing cloth (Buehler Microfiber), rinsed clean with DI water and dried with a fiberless cleaning cloth. In cases where the electrode was precleaned or pre-activated by a multiple-scan experiment the electrode was not polished before each scan; rather, the potentiostat was switched off and the solution was stirred under Ar. Scan rates ranging from 0.02 to 1.5 V s^{-1} were used. Peak potentials were either located by fitting a Lorentzian to ~20 data points close to the maximum current or obtained from the CHI 620E software package (CH Instruments).

3. Results and discussion

Table 1 summarizes the cathodic peak potential, E_{pc}, associated with the two-electron reduction of **1**–**3** determined by us and other investigators under various experimental conditions. Compared to values reported earlier using a GC electrode, potentials obtained with a Pt electrode are much more positive. The differences range from 260 to 630 mV. Namely, the literature results recorded at GC electrodes in KCl electrolyte are found to be shifted by 534 mV for **1** (entry 8), 263 mV for **2** (entry 13), and 630 mV for **3** (entry 16) relative to those recorded at Pt. Moreover, the range of E_{pc} values reported at GC for a given compound under comparable experimental conditions is quite large (ca. 120–240 mV) compared to that at Pt (ca. 10 mV). Although it is not unexpected that peak potentials may change as different electrode materials are employed, the magnitude of the variance is surprisingly large and represents an inconsistency that has not been satisfactorily explained to date.

To better understand these discrepancies, we conducted experiments under conditions identical to those reported in the literature and found that E_{pc} for compound **1** in KCl occurred at a more negative value than at Pt (−0.450 V, entry 3). Upon changing

Table 1
Cathodic peak potentials at 0.1 V s^{-1} from this and previously published work for compounds **1**–**3** at platinum and glassy carbon working electrodes. E_{pc} values from this work represent average values obtained from at least 3 trials.

Entry	Compound	Refs.	Electrode	Electrolyte	E_{pc} (V)[d]
1	**1**	[a]	Pt	KCl	−0.158
2	**1**	[a]	Pt	NaOAc	−0.155
3	**1**	[a]	GC	KCl	−0.450
4	**1**	[a]	GC	PBS[b]	−0.511
5	**1**	[a]	GC	KCl + NaCl	−0.447
6	**1**	[a]	GC	KCl + NaCl	−0.555
7	**1**	[21]	GC	KCl	−0.635
8	**1**	[13]	GC	[c]	−0.689
9	**1**	[22]	GC	KCl	−0.565
10	**2**	[a]	Pt	KCl	0.083
11	**2**	[a]	Pt	NaOAc	0.090
12	**2**	[a]	GC	KCl	0.091
13	**2**	[4]	GC	PBS[b]/KCl	−0.173
14	**3**	[a]	Pt	KCl	0.370
15	**3**	[a]	GC	KCl	−0.122
16	**3**	[21]	GC	KCl	−0.260
17	**3**	[22]	GC	KCl	−0.204

[a] This work.
[b] Phosphate buffered saline solution.
[c] Electrolyte was not specified in Ref. [13].
[d] V vs. Ag/AgCl.

the electrolyte to phosphate buffered saline solution to better mimic physiological conditions, the peak potential was observed at −0.511 V (entry 4), which is closer to literature values, but divergent from results at Pt. Because it was unclear if the change in electrolyte (and specifically the presence of phosphate salts) caused the negative shift, removal of the phosphate salts to give a NaCl/KCl electrolyte mixture produced only a slightly more positive E_{pc} of −0.447 V (entry 5). However, the latter condition exhibited a more negative value (−0.555 V, entry 6) after a 20 h period in a separate run. The difference between the last two potentials, obtained using the same experimental setup and conditions, is worrisome, because changes in peak potential of over 100 mV without an obvious reason cast doubt on the reliability of the measurements.

Similar to results obtained for compound **1** significant differences in E_{pc} values were found for compound **3** with values obtained at Pt being more positive than those reported under identical experimental conditions using a GC electrode. For example, we observed a peak potential at −0.122 V (entry 15), which although relatively close to values of −0.260 and −0.204 V reported previously [21,22], is nearly 500 mV more negative than the platinum electrode result of +0.370 V (entry 14). The E_{pc} value for **2** measured in this work with a GC electrode (entry 12) is equal within ±10 mV to the value obtained at Pt. This agreement is deceiving, however, because E_{pc} values from individual voltammetric trials at an identical scan rate deviate by as much as 47 mV from the average. The lack of precision of peak potential measurements at GC electrodes, which is apparent from the results plotted in Fig. 1, is discussed further below.

Given the puzzling and erratic behavior of measurements at GC electrodes, we questioned whether peak potentials observed for compounds **1**–**3** varied as a function of scan rate in a manner

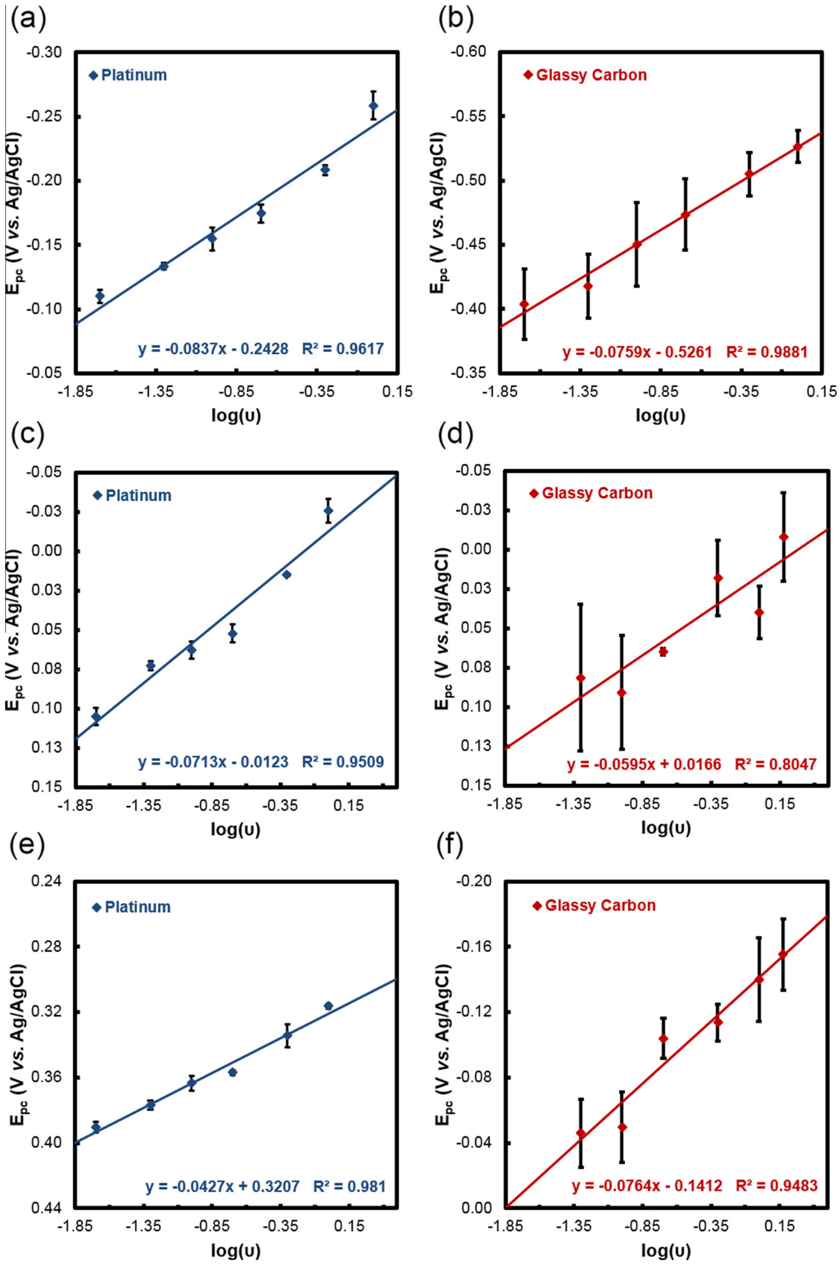

Fig. 1. Plots of E_{pc} (V vs. Ag/AgCl) as a function of log (υ) illustrating the inconsistencies and unpredictability in using a GC electrode (b, d and f) compared to a Pt electrode (a, c and e) for compounds **1**–**3** (from top to bottom). At least three individual trials were conducted at each scan rate leading to the average E_{pc} values shown.

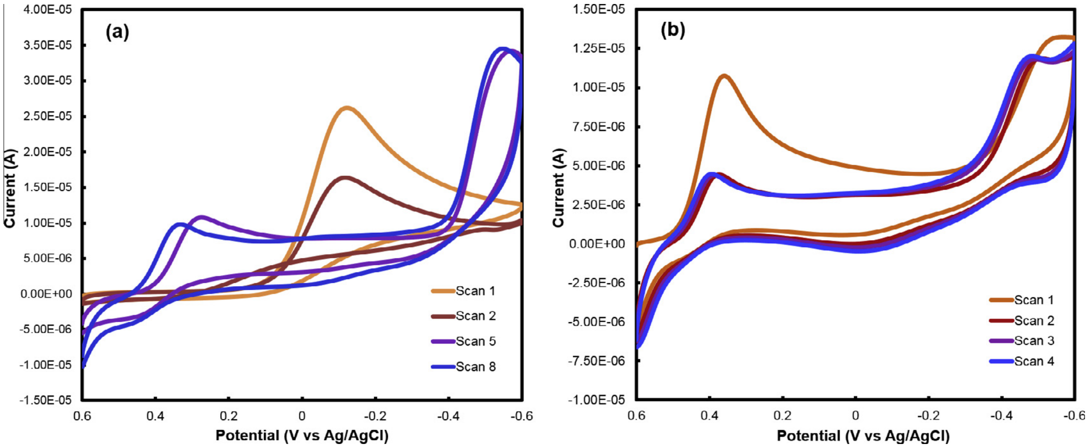

Fig. 2. Multiple cycle CVs ($\upsilon = 0.1\ \mathrm{V\ s^{-1}}$) obtained for **3** at (a) GC electrode (b) Pt electrode in 0.1 M KCl.

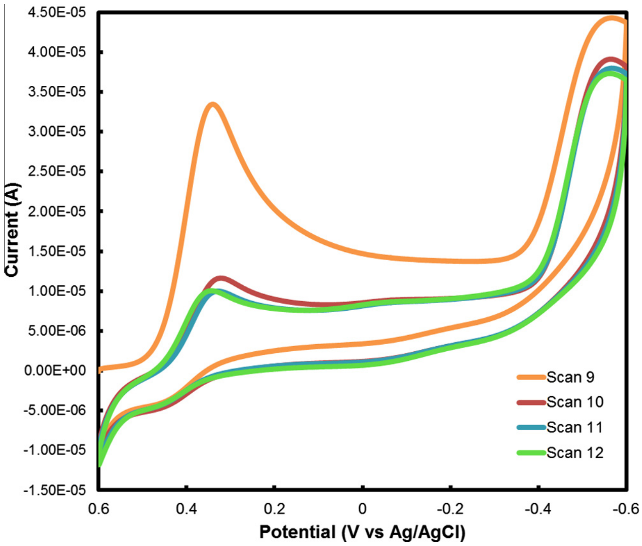

Fig. 3. Multiple CV cycles obtained for **3** at an activated GC electrode allowed to remain in solution, but not re-polished (see text).

consistent with theoretical expectations. For a standard irreversible system, E_{pc} should depend linearly on log (υ), where υ is the scan rate [1]. Fig. 1 compares this dependence for both glassy carbon and platinum electrodes. It is evident that a general linear trend is followed in all cases, but the error bars at each point illustrate how large the deviations are for GC electrode measurements. Specifically, the E_{pc} of **1** deviates by as much as ±33 mV at a scan rate of $0.1\ \mathrm{V\ s^{-1}}$ when a GC electrode is used (Fig. 1b), whereas E_{pc} values measured for **1** at Pt (Fig. 1a) display a maximum deviation from the average of ±11 mV (at $1\ \mathrm{V\ s^{-1}}$). For compound **3**, E_{pc} values at GC vary by as much as ±26 mV at a scan rate of $0.1\ \mathrm{V\ s^{-1}}$ (Fig. 1f) in contrast to a maximum deviation (at $0.5\ \mathrm{V\ s^{-1}}$) of ± 7 mV for Pt (Fig. 1e). Surprisingly, a large negative shift of E_{pc} is not seen for **2** when comparing values obtained at Pt and GC (Fig. 1c and d). Nevertheless, the reliability of the linear E_{pc} versus log (υ) fit is questionable considering the substantial deviations observed at GC for most scan rates. The most notable uncertainty occurs at $0.05\ \mathrm{V\ s^{-1}}$, where the standard deviation is 47 mV and the range of values is 91 mV. Apart from the deceptively linear trend in E_{pc} versus log (υ) plots produced by using average values, it is crucial to note that the imprecise responses at GC electrodes are offset significantly in the negative direction relative to Pt electrode measurements. The differences are as large as 300 mV in the case of compound **1** and 430 mV in the case of compound **3**.

One explanation for the observations described above is based on the interaction of the Pt(IV) complex with the poorly defined surface of the GC electrode during electron transfer, which results in the overall kinetics becoming highly dependent on the specific constitution of the GC surface – specifically, the oxide contaminants on carbon that change both in composition and coverage with time and treatment [36–43]. Generally, these inhomogeneously distributed oxides and other contaminants are introduced most extensively through conventional forms of electrode polishing (i.e., use of alumina slurries), which can imbed contaminants in the microstructure of the carbon surface or create an undefined distribution and thickness of surface oxides that can only be removed through more rigorous forms of pre-treatment, e.g., heat and laser treatments [36,37,40,41]. Even complexes that undergo a purely outer-sphere redox reaction will be affected by a uniform surface film on the electrode; specifically, the electron-transfer rate is slowed by the need for the electron to tunnel through the film between the reactant and the electrode surface [44]. If surface-bound oxides are the main contributors to the observed inconsistencies, we speculate that the GC surface may be activated by repetitive sweeping to highly reducing potentials, which either reduces or reconstitutes the surface oxides. If so, a more consistent carbon surface with a significantly reduced amount of oxide may be prepared.

To test this hypothesis we carried out the multi-scan CV experiments illustrated in Fig. 2, which show the overlay of representative voltammograms obtained for reduction of compound **3** at GC and Pt electrodes. To clarify, the multiple-scan CV experiments allowed scanning over a specified potential window with no delay in between each scan.

The multi-cycle voltammogram obtained with a GC electrode (Fig. 2a) shows an initial cathodic peak potential at −0.122 V vs Ag/AgCl (scan 1). In scan 2 the peak potential shifts only by 5 mV to −0.117 V; however, there is a significant decrease in the peak current caused by the slow diffusion of **3** to the electrode surface. The most dramatic change occurs after scan 2, when E_{pc} moves to much more positive values. This change is illustrated by scan 5, wherein E_{pc} has shifted by nearly 400 mV to 0.276 V. Little further change occurs between scan 5 and scan 8 with the current response attaining a near steady state value and E_{pc} shifting in the positive direction by only 55 mV to 0.331 V. Importantly, once the GC electrode is removed from solution and re-polished, E_{pc} returns to the initial value seen in scan 1.

An interesting feature in the multiple-scan CV shown in Fig. 2a is the eventual appearance of an additional reduction peak at −0.574 V in scan 5, which shifts to −0.549 V in scan 8. Although not confirmed by further experiments, we propose that this peak corresponds to further reduction of the Pt(II) complex formed in the first two-electron reaction. The Pt(0) produced in this reaction may deposit on the carbon surface of the electrode. It is unclear how the electron-transfer kinetics of the Pt(IV)/Pt(II) couple would be affected, but, as we observe faster kinetics at Pt electrodes, it is plausible that deposition of Pt(0) on GC would accelerate the electron-transfer rate of the Pt(IV) prodrugs. However, in separate experiments (not shown here) we have observed that GC becomes activated even when voltammetric scans are limited to potentials at which the two-electron reduction to Pt(0) is not reached. Therefore, the change in response of GC electrodes upon repetitive potential cycling most likely arises from an alteration of the carbon surface and not from the deposition of Pt(0).

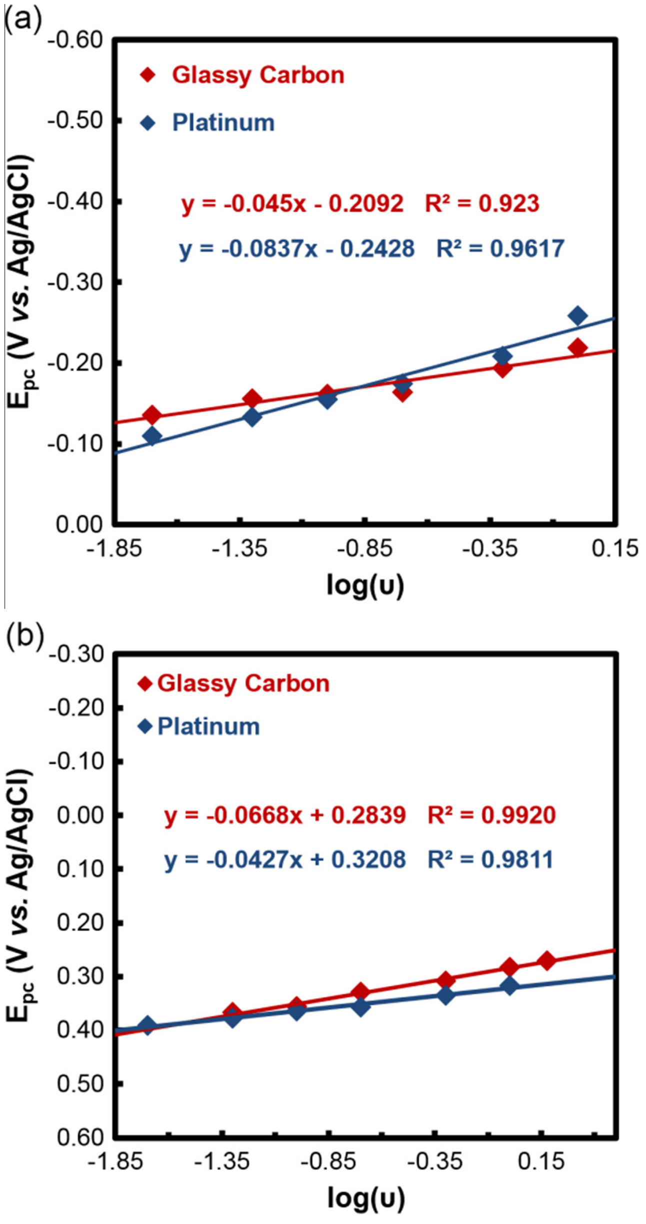

Fig. 4. Plots of E_{pc} (V vs. Ag/AgCl) as a function of log (υ) illustrating the improved agreement between Pt and activated GC electrode behavior for compounds **1** (a) and **3** (b).

In contrast to the results at GC electrodes, the CV in Fig. 2b clearly demonstrates that pre-trial polishing and multiple scanning have a much smaller influence on the location of the Pt(IV) peak potential at Pt electrodes. E_{pc} appears at 0.359 V vs Ag/AgCl during the first scan, which is 28 mV more positive even than the final peak potential seen after multiple-scan activation of the GC electrode (Fig. 2a). Moreover, the behavior at platinum is changed only slightly by multiple scanning as indicated by the relatively small positive shift in E_{pc} to 0.394 V in the fourth scan of Fig. 2b. It should be noted that even after activation via multiple scans to reducing potentials, E_{pc} values obtained with GC never completely achieve the more positive potentials found when employing Pt as the working electrode.

The literature suggests that conventional polishing increases the amount of oxides on a GC surface [36–38,44]. Thus, we assume that the unpolished GC electrode following multiple-scan activation should remain activated, even after switching off the potentiostat, replenishing the concentration of Pt(IV) prodrug adjacent to the electrode surface, and restarting the experiment. The resulting multiple-scan CV is presented in Fig. 3 where the initial E_{pc} for reduction of **3** is found at a significantly more positive potential of 0.341 V vs Ag/AgCl compared to the initial value of −0.122 V shown in Fig. 2a. This result demonstrates that the glassy carbon surface remains activated in the absence of an applied potential even when the solution undergoes additional stirring or degassing with argon. The phenomenon of GC surface activation is most apparent for **1** and **3**, where cathodic peak potential differences between Pt and untreated GC are significant. Fig. 4a and b demonstrate the much improved agreement in E_{pc} values and E_{pc} vs. log (υ) responses achieved by activation of the GC electrode for these two complexes. An additional improvement revealed by the multiple-scan activation procedure is the marked increase in precision of the E_{pc} values obtained at GC for each scan rate. Table 2 enumerates the improvement in standard deviation of the cathodic peak potential determined from three separate trials for compound **3**.

A final consideration is the accuracy with which an experimental parameter approximates the reduction potential of a Pt(IV) prodrug. The fundamental quantity is the thermodynamic potential for addition of one electron to the Pt(IV) center; i.e., $E_{1,s}°$ in Scheme 1. Previously, we determined $(E_{1,s}°)_{expt}$ by applying Savéant's analysis of irreversible bond-breaking electron-transfer reactions to the two-electron reductions of **1**–**3** using variable scan rate cyclic voltammetry [2]. As shown in Table 3 these potentials are in very good agreement with values obtained by density functional theory (DFT) calculations, $(E_{1,s}°)_{comput}$, for the same electrochemical process. However, neither of these approaches is routine, and experimentalists understandably may wish to employ a simpler methodology without sacrificing accuracy. Table 3 shows that voltammetric peak potentials obtained at a scan rate of 0.1 V s^{-1} at both Pt and activated GC electrodes provide a reasonably accurate approximation of the desired thermodynamic

Table 2
Standard deviations ($n = 3$) for E_{pc} values (in V) obtained for **3** at various scan rates with the use of glassy carbon, activated glassy carbon, and platinum working electrodes.

Scan rate (V s^{-1})	Standard deviation (in V)		
	GC	GC-activated	Pt
0.05	0.021	0.002	0.003
0.1	0.012	0.003	0.005
0.2	0.021	0.003	0.002
0.5	0.011	0.005	0.007
1	0.026	0.002	0.002
1.5	0.022	0.001	–

Table 3

Comparison of potentials for reduction of Pt(IV) prodrugs **1**–**3** (V vs. Ag/AgCl).

Compound	$E_{\text{pc, Pt}}$[a]	$E_{\text{pc, GC-Activated}}$[a]	$E_{\text{pc, GC-Unactivated}}$[a]	$(E_{1,s}°)_{\text{expt}}$[b]	$(E_{1,s}°)_{\text{comput}}$[c]
1	−0.158	−0.162	−0.450	−0.216	−0.200
2	0.083	0.092	0.091	0.100	0.199
3	0.370	0.344	−0.122	0.331	0.254

[a] This work; average cathodic peak potential values obtained at 0.1 V s^{-1}.

[b] Standard reduction potential in Scheme 1 obtained by Savéant analysis of the irreversible two-electron reduction at a Pt electrode; See Ref. [2].

[c] Standard reduction potential in Scheme 1 obtained by DFT calculations; See Ref. [2].

parameter. Unactivated GC electrodes are much less satisfactory in this regard and also are compromised by poor measurement precision. Thus, measurements at Pt or properly activated GC electrodes are recommended for electrochemically assessing the effectiveness of Pt(IV) antitumor prodrugs.

4. Conclusion

We have studied the electrochemical reduction of six-coordinate Pt(IV) complexes, which exhibit an irreversible cathodic response in CV measurements upon insertion of two-electrons and loss of two axial ligands to form square-planar Pt(II) complexes. Heretofore, most investigators have resorted to reporting the cathodic peak potential, E_{pc}, obtained at a GC electrode as a substitute for the standard redox potential, $E°$, in assessing the efficacy of these antitumor prodrug compounds. However, we recently demonstrated that reduction potentials determined in this manner are seriously in error when compared to consistent values obtained by measurements at platinum electrodes and by quantum chemical calculations. It is shown here that conventionally used GC electrodes are the source of serious errors and inconsistencies in measuring reduction potentials for Pt(IV) prodrugs. Potentials obtained at Pt electrodes are more positive by ca. 200–600 mV for compounds **1**–**3** compared to values reported in the current literature where GC is employed. Furthermore, the significant imprecision found among individual GC-derived values reduces confidence in results obtained by this approach, although linear E_{pc} vs log (υ) responses generally are observed.

It is believed that ineffective interaction of Pt(IV) prodrug complexes with the ill-defined surface of unactivated glassy carbon electrodes results in slow electron transfer due to the need for electrons to tunnel through an ever-present oxide film on the electrode surface. We propose a simple experimental solution that produces more consistent and reproducible data with GC electrodes, whereby the surface is activated through repetitive cycling to negative potentials, which should liberate oxide contaminants and generate a more consistent carbon surface. Large positive shifts in E_{pc} are observed on GC as early as the second of a series of multiple scans, and, if an activated electrode is left in solution during stirring or argon purging, the more accurate positive peak potentials are retained. However, a GC electrode repolished in the laboratory ambient reverts to more negative, erroneous E_{pc} values. Results obtained with platinum electrodes are largely uninfluenced by polishing or multiple scan treatments. Thus, it is recommended that Pt or appropriately activated GC electrodes be used for redox potential measurements of Pt(IV) prodrug compounds.

Notes

The authors declare no competing financial interests.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.poly.2015.09.040.

References

[1] A.J. Bard, L.R. Faulkner, Electrochemical Methods, John Wiley & Sons Inc, New York, 1980.
[2] M.C. McCormick, K. Keijzer, A. Polavarapu, F.A. Schultz, M.-H. Baik, J. Am. Chem. Soc. 136 (2014) 8992.
[3] R.P. Feazell, N. Nakayama-Ratchford, H. Dai, S.J. Lippard, J. Am. Chem. Soc. 129 (2007) 8438.
[4] S. Dhar, S.J. Lippard, Proc. Natl. Acad. Sci. U.S.A. 106 (2009) 22199.
[5] C.M. Giandomenico, M.J. Abrams, B.A. Murrer, J.F. Vollano, M.I. Rheinheimer, S. B. Wyer, G.E. Bossard, J.D. Higgins, Inorg. Chem. 34 (1995) 1015.
[6] M.D. Hall, T.W. Hambley, Coord. Chem. Rev. 232 (2002) 49.
[7] M.D. Hall, H.R. Mellor, R. Callaghan, T.W. Hambley, J. Med. Chem. 50 (2007) 3403.
[8] K. Lemma, J. Berglund, N. Farrell, L.I. Elding, J. Biol. Inorg. Chem. 5 (2000) 300.
[9] S. Dhar, N. Kolishetti, S.J. Lippard, O.C. Farokhzad, Proc. Natl. Acad. Sci. U.S.A. 108 (2011) 1850.
[10] S. Dhar, Z. Liu, J.R. Thomale, H. Dai, S.J. Lippard, J. Am. Chem. Soc. 130 (2008) 11467.
[11] N.J. Wheate, S. Walker, G.E. Craig, R. Oun, Dalton Trans. 39 (2010) 8113.
[12] J.F. Hartwig, S.J. Lippard, J. Am. Chem. Soc. 114 (1992) 5646.
[13] L. Chen, P. Foo Lee, J.D. Ranford, J.J. Vittal, S. Ying Wong, J. Chem. Soc., Dalton Trans. (1999) 1209.
[14] T. Nakai, M. Ando, Y. Okamoto, K. Ueda, N. Kojima, J. Inorg. Biochem. 105 (2011) 1.
[15] M.R. Reithofer, A.K. Bytzek, S.M. Valiahdi, C.R. Kowol, M. Groessl, C.G. Hartinger, M.A. Jakupec, M. Galanski, B.K. Keppler, J. Inorg. Biochem. 105 (2011) 46.
[16] J. Platts, G. Ermondi, G. Caron, M. Ravera, E. Gabano, L. Gaviglio, G. Pelosi, D. Osella, J. Biol. Inorg. Chem. 16 (2011) 361.
[17] J.A. Platts, D.E. Hibbs, T.W. Hambley, M.D. Hall, J. Med. Chem. 44 (2000) 472.
[18] L. Ellis, H.M. Er, T.W. Hambley, Aust. J. Chem. 48 (1995) 793.
[19] S. Choi, C. Filotto, M. Bisanzo, S. Delaney, D. Lagasee, J.L. Whitworth, A. Jusko, C. Li, N.A. Wood, J. Willingham, A. Schwenker, K. Spaulding, Inorg. Chem. 37 (1998) 2500.
[20] J.J. Wilson, S. Lippard, J. Inorg. Chem. 50 (2011) 3103.
[21] M.D. Hall, S. Amjadi, M. Zhang, P.J. Beale, T.W. Hambley, J. Inorg. Biochem. 98 (2004) 1614.
[22] P. Gramatica, E. Papa, M. Luini, E. Monti, M. Gariboldi, M. Ravera, E. Gabano, L. Gaviglio, D. Osella, J. Biol. Inorg. Chem. 15 (2010) 1157.
[23] A.R. Battle, R. Choi, D.E. Hibbs, T.W. Hambley, Inorg. Chem. 45 (2006) 6317.
[24] J.M. Savéant, J. Am. Chem. Soc. 109 (1987) 6788.
[25] C.P. Andrieux, A. Le Gorande, J.M. Savéant, J. Am. Chem. Soc. 114 (1992) 6892.
[26] J.M. Savéant, J. Am. Chem. Soc. 114 (1992) 10595.
[27] J.M. Savéant, Acc. Chem. Res. 26 (1993) 455.
[28] C.P. Andrieux, E. Differding, M. Robert, J.M. Savéant, J. Am. Chem. Soc. 115 (1993) 6592.
[29] C.P. Andrieux, M. Robert, F.D. Saeva, J.-M. Savéant, J. Am. Chem. Soc. 116 (1994) 7864.
[30] J.M. Savéant, J. Phys. Chem. 98 (1994) 3716.
[31] J.-M. Savéant, J. Electroanal. Chem. 485 (2000) 86.
[32] J.-M. Savéant, Adv. Phys. Org. Chem. (2000) 117.
[33] C. Costentin, M. Robert, J.-M. Savéant, Chem. Phys. 324 (2006) 40.

[34] S. Antonello, M. Musumeci, D.D.M. Wayner, F. Maran, J. Am. Chem. Soc. 119 (1997) 9541.
[35] F. Maran, D.D.M. Wayner, M.S. Workentin, Adv. Phys. Org. Chem. 36 (2001) 85.
[36] R.L. McCreery, in: A.J. Bard (Ed.), Electroanal. Chem., vol. 17, Dekker, NY, 1991, p. 221.
[37] S. Ranganathan, T.-C. Kuo, R.L. McCreery, Anal. Chem. 71 (1999) 3574.
[38] K.G. Ray III, R.L. McCreery, J. Electroanal. Chem. 469 (1999) 150.
[39] M.T. McDermott, C.A. McDermott, R.L. McCreery, Anal. Chem. 65 (1993) 937.
[40] I.-F. Hu, D.H. Karweik, T. Kuwana, J. Electroanal. Chem. 188 (1985) 59.
[41] R. Rice, C. Allred, R. McCreery, J. Electroanal. Chem. 263 (1989) 163.
[42] K.R. Kneten, R.L. McCreery, Anal. Chem. 64 (1992) 2518.
[43] R.J. Rice, N.M. Pontikos, R.L. McCreery, J. Am. Chem. Soc. 112 (1990) 4617.
[44] R.L. McCreery, Chem. Rev. 108 (2008) 2646.