

R74-32

TECHNICAL LIBRARY
U. S. ARMY
NATICK LABORATORIES
NATICK, MASS. 01760

Rate Constants of Electron Transfer Processes in Solution: Dependence on the Redox Potential of the Acceptor

ONE-ELECTRON oxidation-reduction reactions have been established in several enzymatic reactions, and electron transport has been found to be necessary in phosphorylation and mitochondrial systems¹⁻⁴. The role of semiquinone radicals as active agents in biochemical electron transfer reactions has been indicated^{1,2}, and correlations between the redox potential

of the quinones and their effectiveness in catalysing a particular type of phosphorylation reaction have been suggested^{1,2,5}. This principle has never been demonstrated quantitatively by chemical kinetics.

The redox reactions of a number of organic free radicals against menaquinone as acceptor have been studied⁶⁻¹⁰. The rate constants k for electron transfer from some of these radicals to different acceptors as a function of the redox potential (E^{*1}) of the acceptors is the subject of the study described here. The fast-reaction technique of pulse radiolysis was used^{10,11} for generating the free radicals in water (a) by reaction of OH radicals with some substrates (in the presence

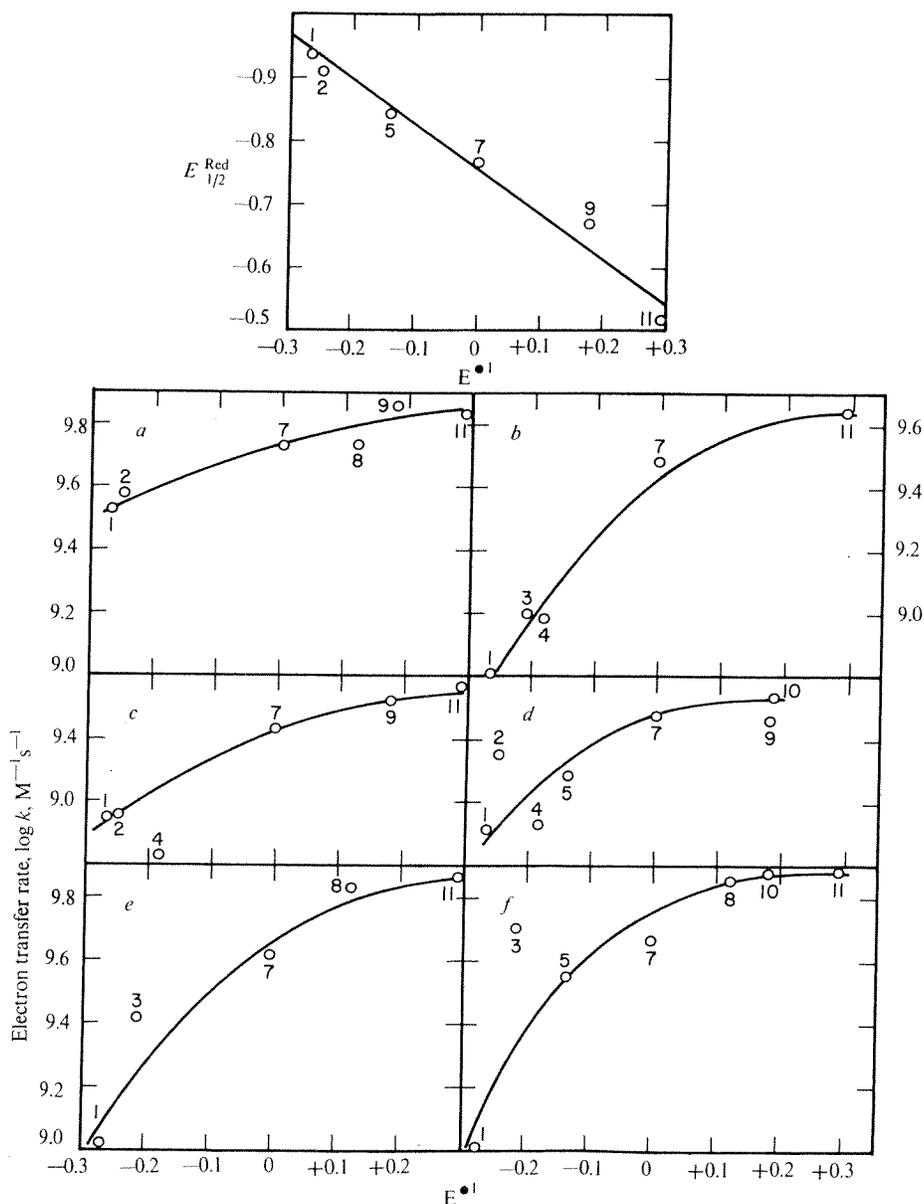


Fig. 1 Dependence of $\log k$, the electron transfer rate constants of various free radicals (produced by reaction of substrate with e_{aq}^-) upon the E^{*1} values of the acceptors. The numbers refer to the acceptor used. Included is the correlation between E^{*1} and the half-wave reduction potential of some of the acceptors (taken from ref. 17). *a*, Nicotinamide, pH 7.0; *b*, NAD⁺, pH 6.0; *c*, N-ethyl maleimide, pH 6.0; *d*, acetate, pH 9.2; *e*, Co²⁺, pH 7.0; *f*, Cd²⁺, pH 7.0.

of N_2O to convert e_{aq}^- into OH radicals), (b) by reaction of e_{aq}^- with other substrates (in argon and ~ 1.0 M *t*-butyl alcohol to scavenge⁹ the OH radicals).

The acceptor concentration was $\sim 5 \times 10^{-5}$ M for quinones and $\sim 1 \times 10^{-4}$ M for other acceptors. The [radical] was kept at $\geq 5\%$ [acceptors]. The k values were determined at $\sim 22^\circ$ C

Fig. 2 Dependence of $\log k$, the electron transfer rate constants of various free radicals (produced by reaction of substrate with OH radicals) on the E^{*1} values of the acceptors. a, Formate, pH 7.0; b, isopropyl alcohol, pH 7.0; c, cytosine, pH 7.0; d, glycine, pH 8.0; e, triglycine, pH 10; f, glycollic acid, pH 7.0.

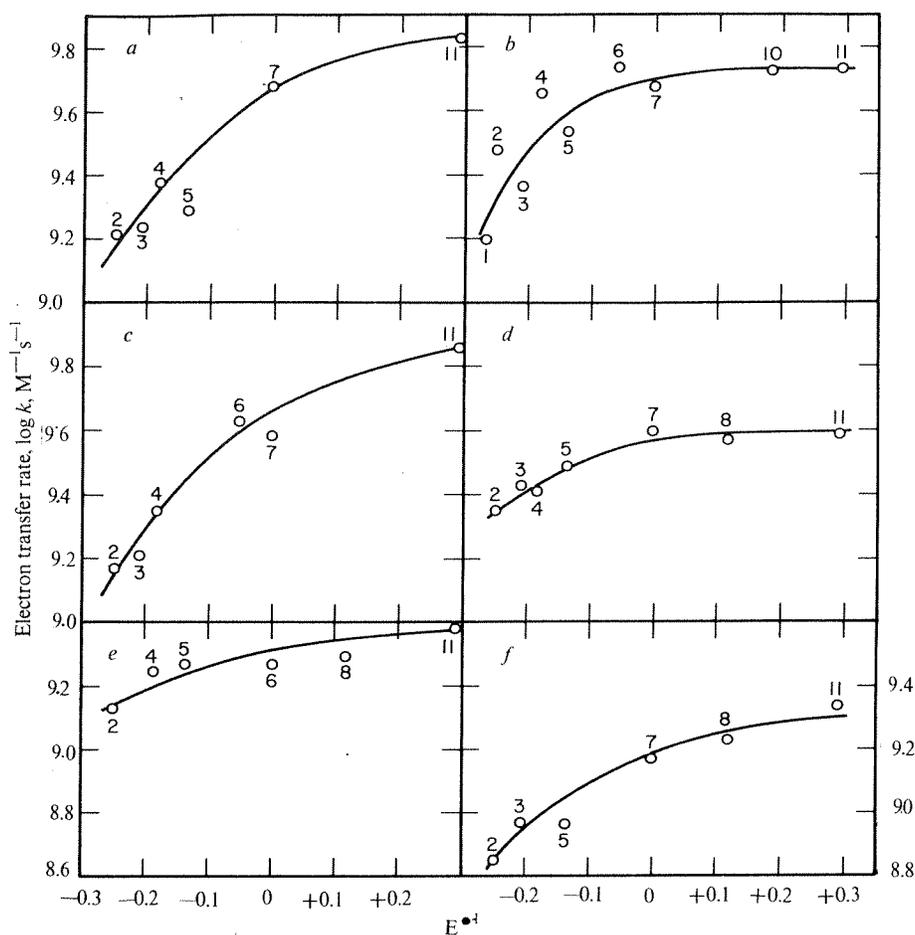


Table 1 Rate Constants of One-Electron Oxidation-reduction Reactions of Free Radicals with Various Acceptors in Aqueous Solution

Substrate	Donor radical	Rate of electron transfer, $k \times 10^{-9} \text{ M}^{-1} \text{ s}^{-1} *$										
		①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪
		-0.266	-0.250	-0.208	-0.184	-0.139	-0.055	+0.002	+0.118	+0.176	+0.180	+0.293
Formate	$\bullet\text{CO}_2 \ddagger$	—	1.65	1.71	2.40	1.95	†	4.80	†	—	†	6.60
Isopropyl alcohol	$(\text{CH}_3)_2\dot{\text{C}}\text{OH} \ddagger$	1.62	3.04	2.30	4.60	3.40	5.55	4.76	†	—	4.24	5.40
Cytosine	$\bullet\text{C-OH} \ddagger$	—	1.48	1.61	2.26	†	4.29	3.80	†	—	†	7.20
Triglycine	$\text{H}_2^+-\text{Gly-Gly-NH}\dot{\text{C}}\text{OO}^- \ddagger$	—	1.36	—	1.79	1.88	—	1.88	1.97	—	—	2.46
Glycine	$\text{NH}_2\dot{\text{C}}\text{HCOO}^- \ddagger$	—	2.25	2.72	2.56	3.12	†	4.00	3.30	—	†	3.90
Glycollic acid	$\text{OH}\dot{\text{C}}\text{HCOO}^- \ddagger$	—	0.71	0.93	—	0.91	—	1.47	1.69	—	†	2.20
Nicotinamide	$\bullet\text{NH} \S$	3.50	3.80	—	—	†	—	5.40	5.45	7.25	—	7.00
NAD ⁺	$\bullet\text{NAD} \S$	0.41	—	1.00	0.96	—	—	3.10	—	†	—	4.40
N-ethyl maleimide	$\bullet\text{NEM}^- \S$	0.83	0.82	—	0.46	—	—	3.00	—	4.40	—	5.50
Acetoacetate	$\text{CH}_3\dot{\text{C}}(\text{O}^-)\text{CH}_2\text{COO}^- \S$	0.67	2.10	†	0.72	1.53	0.73	3.70	†	3.34	4.80	†
Cobalt sulphate	$\text{CO}^+ \S$	1.05	†	2.55	†	†	†	4.10	6.83	†	†	7.35
Cadmium sulphate	$\text{Cd}^+ \S$	1.03	†	5.10	†	3.57	†	4.68	7.35	†	7.80	7.70

* See text for acceptor corresponding to each number. $E^{*1}(\text{pH } 7.0)$ used as the redox potential.

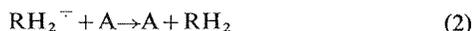
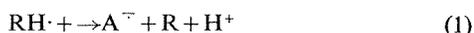
† Slow thermal reaction occurring in this system.

‡ Donor radical produced by reaction of substrate with OH radicals.

§ Donor radical produced by reaction of substrate with e_{aq}^- .

by following (a) the formation kinetics of the semiquinone radical anions of the quinones (at 400 nm) and of riboflavin (at 560 nm¹³); (b) the disappearance kinetics of MnO₄⁻ at 545 nm and of ferricyanide at 420 nm. From the pseudo-first order rates, the second order rates were determined. The following acceptors were studied: 9,10-anthraquinone (①, -0.266), 9,10-anthraquinone-2-sulphonate (②, -0.250), riboflavin (③, -0.208), 9,10-anthraquinone-2,6-disulphonate (④, -0.184), 2-hydroxy-1,4-naphthaquinone (⑤, -0.139), ferricyanide (⑥, -0.055), menaquinone (⑦, 0.002), 1,4-naphthaquinone-2-sulphonate (⑧, 0.118), 2,5-dimethyl-*p*-benzoquinone (⑨, 0.176), MnO₄⁻ (⑩, 0.180), and *p*-benzoquinone (⑪, 0.293). The *E*^{•1} values (*p*H=7.0, 25° C) given in parenthesis were from ref. 14.

The electron transfer reactions taking place can be represented as:



The *p*K_a of the semiquinones^{10,15,16} used lie in the range 4.0–5.0: $\text{AH}\cdot \rightleftharpoons \text{A}^- + \text{H}^+$. The results are presented in Table 1 and Figs 1 and 2. In addition, the *k* values of CH₂OH, (CH₃)₂COH, NH₂CHCOO⁻ and Cd⁺ to NAD⁺ (*E*^{•1} = -0.320) as an acceptor were found to be 1.0 × 10⁹, 1.0 × 10⁹, 1.5 × 10⁹ and 2.9 × 10⁹ M⁻¹ s⁻¹, respectively.

From the experimental results (rate values ± 10%): (a) a quantitative correlation appears between the *k* values from many free radicals and the *E*^{•1} of various electron acceptors (quinones, riboflavin, NAD⁺, ferricyanide and MnO₄⁻); (b) the rate is expected to increase with increase in Δ*E*^{•1} between the donor radical and the acceptor (as indicated by the different slopes for the various radical donors); (c) the half-wave reduction potential *E*_{1/2}^{red} of the radical is probably a better parameter to use but only limited data are available¹⁷; there is a direct correlation, however, between *E*^{•1} and *E*_{1/2}^{red} (see Fig. 1), as well as between the electron affinity and *E*_{1/2}^{red} (ref. 18); (d) as there is a good linear relationship between the

redox potential and the energy of the highest occupied orbital¹⁹ (calculated by LCAO-MO method) one electron should be removed (or added) from that orbital in the rate determining step.

In conclusion, these results show that, to a first approximation, the rate constants for electron transfer processes from free radicals to various acceptors are proportional to the redox potential of the acceptor. As redox reactions are used extensively to introduce or withdraw electrons in biochemical reactions, such correlations can be used to predict the course of various competitive reactions, as well as to derive an approximate *E*^{•1} value for a compound.

P. S. RAO
E. HAYON

Pioneering Research Laboratory,
US Army Natick Laboratories,
Natick, Massachusetts 01760

Received January 8, 1973.

- ¹ *Electron and Coupled Energy Transfer in Biological Systems* (edit. by King, T. E., and Klingenberg, M.), 1, parts A and B (Dekker, New York, 1971 and 1972).
- ² *Biochemistry of Quinones* (edit. by Morton, R. A.) (Academic Press, New York, 1965).
- ³ Taube, H., *Electron Transfer Reactions of Complex Ions in Solution* (Academic Press, New York, 1970).
- ⁴ Reynolds, W., and Lumry, R., *Mechanisms of Electron Transfer Reactions* (Ronald Press, New York, 1966).
- ⁵ Trebst, A., and Eck, H., *Z. Naturforsch.*, **16b**, 44 (1961).
- ⁶ Simic, M., and Hayon, E., *Int. J. Radiat. Biol.*, **20**, 589 (1971).
- ⁷ Hayon, E., and Simic, M., *Radiat. Res.*, **50**, 464 (1972).
- ⁸ Simic, M., and Hayon, E., *Int. J. Radiat. Biol.*, **22**, 507 (1972).
- ⁹ Hayon, E., and Simic, M., *J. Amer. Chem. Soc.* (in the press).
- ¹⁰ Rao, P. S., and Hayon, E., *Biochim. Biophys. Acta* (in the press).
- ¹¹ Simic, M., Neta, P., and Hayon, E., *J. Phys. Chem.*, **73**, 3794 (1969).
- ¹² Keene, J. P., Black, E. D., and Hayon, E., *Rev. Sci. Instrum.*, **40**, 1199 (1969).
- ¹³ Land, E. J., and Swallow, A. J., *Biochemistry*, **8**, 2117 (1969).
- ¹⁴ *Handbook of Biochemistry*, J. 33 (Chemical Rubber Co., 1970).
- ¹⁵ Hayon, E., Ibata, T., Lichtin, N. N., and Simic, M., *J. Phys. Chem.*, **76**, 2072 (1972).
- ¹⁶ Willson, R. L., *Chem. Comm.*, 1249 (1971).
- ¹⁷ Peover, M. E., *J. Imp. Coll. Chem. Soc.*, 4540 (1962).
- ¹⁸ Briegleb, G., *Angew. Chem.*, **3**, 617 (1964).
- ¹⁹ Fueno, T., Lee, T., and Eyring, H., *J. Phys. Chem.*, **63**, 1940 (1959).