Factors Governing the Herbicidal Properties of Paraquat, 1,1'-Dimethyl Bipyridylium Dichloride

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Summary:The factors earlier proposed as being probably responsible for the herbicidal activity of paraquat (1,1'dimethyl bipyridylium dichloride) family were re-examined in the light of the existence of the higher reduction product MB: and the relative rates of the reaction of the two reduction products of MB^{2+} with oxygen. Since in the case of paraquat it has earlier been proposed that adsorptivity may be a factor which influences its herbicidal activity, the reaction of the two reduction products $MB^{\cdot+}$ and MB: with oxygen were studied in adsorbed state.The role of MB: is thus highlighted in the present study.

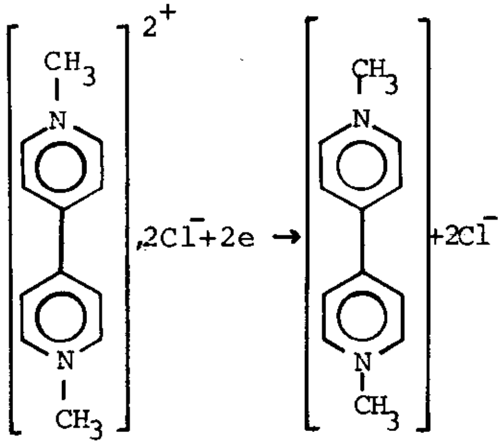
Ever since Brian [1] discovered the new herbicide paraquat: 1,1'-dimethyl bipyridylium dichloride, $MBCl_2$, there have been attempts to explain the mechanism of its activity [2]. Through some electrochemical, kinetic and photochemical studies, it was proposed that the monocation radical $MB^{\cdot+}$ of paraquat was the sole active form responsible for herbicidal activity [3-5].

On the basis of electrochemical and some kinetic studies [3-5] three factors have been proposed as being probably responsible for the herbicidal activity of this class of compound. These factors being (a) the ease of (reversible) one electron reduction (b) sensitivity towards oxygen of the cation radicals and (c) the adsorptivity of the parent compound or cation radical [3a].

Much emphasis has been put on condition (b) above, the sensitivity of the cation radicals towards oxygen [4,5]. The rate constant for the reaction of $MB^{\cdot+}$ with oxygen in water under homogeneous conditions has been reported [5,6] to be $10^8 M^{-1}s^{-1}$. No consideration has so far been given to the possible different rate of reaction of $MB^{\cdot+}$ with oxygen under the condition (c) mentioned above.

It may be pointed out that biological reactions occur under heterogeneous as well as homogeneous conditions. A number of electrochemical studies have been made on DNA and related compounds from this view point [7].

Since in the case of paraquat it has been proposed that adsorptivity may be a factor which influences its herbicidal activity [3a] and, as mentioned above, many biological reactions do occur at membrane interfaces (adsorbed state) [7], it is necessary to know the rate of reaction of $MB^{\cdot+}$ with oxygen under adsorbed state. There is some indication that $MB^{\cdot+}$ does undergo a reaction with oxygen at considerable lower rates under adsorbed state, compared to that under homogeneous conditions [8]. At the same time no attempt has so far been made to study the higher reduction products of MB^{2+}



(i.e.MB^{2+} 2e ------ MB:) vis a vis their role, if any, in herbicidal activity. Our studies, thus, in this regard, propose MB: as an intermediate to be considered alongwith MB^{+} for explaining the herbicidal activity of paraquat in vivo.

The electrochemical (Mohammad - Nicholson-Shain) method of studying the reaction of reactive intermediates [9] when applied to the reaction of $MB.^{+}$ with oxygen (equation 2)

$$MB^{+} + e \rightleftharpoons MB.^{+} \quad (1)$$

$$MB^{+} + O_2 \longrightarrow [MB.^{+}O_2] \quad (2)$$

$$[MB^{+}\ O_2) \longrightarrow MB.^{2+} + O^{-}_{2}$$

establishes that $MB.^{+}$ reacts with O_2 in water, on a mercury drop surface (i.e. in adsorbed state) with rate constant 20 $M^{-1}\ s^{-1}$. At gold (disc) surface (i.e. less adsorption) the rate constant is of the order of $10^{3}\ M^{-1}\ s^{-1}$, (while under homogeneous conditions the rate constant [6] is $10^{8} M^{-} s^{-1}$, as mentioned before). This slow reaction of $MB.^{+}$ with O_2 in adsorbed state has confirmed the observation [8] mentioned above. It is apparent that surface reaction of oxygen and $MB.^{+}$ is too slow to be very effective.

In contrast the reaction of MB: with oxygen (eqn.4) is quite fast

$$MB.^{+} + e \rightleftharpoons MB: \quad (3)$$

$$MB: + O_2 \longrightarrow (MB:\ O_2) \quad (4)$$

$$[MB:O_2] \longrightarrow MB^{2+} + \text{or } MB^{2+} + 2O^{-}_{2}.$$

The rate constant for the reaction at mercury and gold surfaces are of the order of $10^{3}\ M^{-1}\ s^{-1}$. Under homogeneous condition, the reaction should, then, be diffusion controlled. Thus it is obvious that MB: could take part as intermediate in the reaction related to herbicidal activity.

MB: may be produced directly under sunlight (photochemical reduction). It has been demonstrated that when paraquat is immobilized in a matrix of polyvinyl alcohol and irradiated with U.V. light, MB: is produced [8] (eqn.5). Thus there is a more than likely chance of production of MB: in adsorbed state in plants. MB: can also be produced through disproportionation (eqn. 6) [10].

$$MB^{2+} + 2e \rightleftharpoons MB: \quad (5)$$

$$2MB.^{+} \longrightarrow MB: + MB^{2+}. \quad (6)$$

Paraquat seems to exert its herbicidal activity in the chloroplast where it is primarily reduced in the region of photosystem I of photosynthetic electron transport. Thus the production of MB: through direct two electron photochemical reduction, as mentioned above, could be considered of little consequence in vivo. The other route (eqn.6) depends upon the disproportionation constant which is generally low [10]. Nevertheless, if adsorptivity is considered to be a definite factor towards herbicidal property of this class of compounds [3a] , the possibility of the occurrence of sufficient concentration of MB: and hence its role may not be overlooked.

It has been pointed out [3a] that the active moiety in the mechanism of herbicidal activity may be the superoxide ion which, even at low concentration (10^{-8}M) will lead to cellular damage. The superoxide ion is supposed to be produced through the electron transfer from $MB.^+$ to O_2 (eqn.2) or MB: to O_2 (eqn.4). Since no catalytic current was observed in the electrochemical investigations, (eqns. 1-4), it may be concluded that, at first, an adduct of the reduced species ($MB.^+$ or MB:) and oxygen is produced in the adsorbed state. Whether the same is true in vivo is yet to be confirmed.

Taking all the aspects into consideration the proposed factors governing the herbicidal activity of paraquat emerging from the earlier work are (a) the ease of reduction of MB^{2+} (b) building sufficient concentration of $MB.^+$ and MB: (c) adsorptivity of the parent compound and its products and (d) sensitivity of MB^+ alongwith that of MB: towards oxygen.

Experimental

Chemical

Paraquat (1,1'-dimethyl bipyridylium dichloride) was supplied by ICI Runcorn, U.K. Water was triple distilled. Lithium chloride used as supporting electrolyte was purified according to Perrin [11].

Commercial nitrogen from tank was purified by passing through vanadous traps.

Instrumentation:

A Health EW 402 polarographic system was used along with a Tektronix function generator EC 501 and a storage oscilloscope. A Beckman strip chart recorder was used for recording the C-V curves. A saturated calomel electorde was used as reference electrode. Other details have been described earlier [10].

Measurements of Rate Constants.

One of the techniques [9] developed in our laboratory for the study of fast reactions (of reactive intermediates) was employed in the present case. This is based upon the theory of stationary electrode polarography and is called the Mohammad-Nicholson-Shain method [9,10]. In this technique a reactive intermediate R is generated by the electrochemical reduction (or oxidation) of a reducible (oxidizable) compound at a stationary electrode in the absence and subsequently in the presence of a reactant A. The current-voltage curve is recorded in each case and from the shift in the peak potential E_p on the addition of large excess of reactant A, the bimolecular rate constant k_2 is calculated (eqn. 7-10) as follows:

$$O + e \rightleftharpoons R \qquad (7)$$

$$R + A \xrightarrow{k} \text{product (s)} \qquad (8)$$

$$k_2 = k/\,(A) \qquad (9)$$

$$E_p = E_{\frac{1}{2}} - 0.026\ (0.780 - 1.51 \log k_{/a},) \qquad (10)$$

at 25 , a=nFV/RT., V being the rate of scan

$MB.^+$ and MB: were generated at the hanging mercury drop electrode (eqns. 1&3) as two steps single electron transfer. Completely reversible waves were recorded in the absence of oxygen. The reduction waves were again recorded in the presence of oxygen under pseudo first order conditions (see eqns. 2,4 and 8). In this case the anodic peaks(s) disappeared and cathodic peak(s) shifted anodically. From this shift and using equations (10) and (9), k_2 were calculated.

Furthermore, the concentration of the salt was lowered gradually to the order to 10^{-6}M and effect of oxygen on the reduction peak(s) was noted. The effect on the reduction peak(s) due to the reaction of these reactive intermediates ($MB.^+$ and MB:) were pronounced and gave approximate values of the rate constants which were consistent with those obtained by the method described above. The concentration of oxygen in the solution was determined by the method of peak current and solubility. The result was consistent with those obtained using the gas-liquid chromatography method.

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