Journal of Hazardous Materials 164 (2009) 1089–1097

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Chlorine dioxide reaction with selected amino acids in water

Sergio Navalon, Mercedes Alvaro, Hermenegildo Garcia*

Department of Chemistry, Universidad Politécnica de Valencia, Camino de Vera S/N, 46022 Valencia, Spain

ARTICLE INFO

Article history:
Received 1 June 2007
Received in revised form 3 September 2008
Accepted 4 September 2008
Available online 7 September 2008

Keywords:
Chlorine dioxide
Amino acids
Reaction mechanism

ABSTRACT

Chlorine dioxide is a hypochlorite alternative disinfectant agent. In this context, we have determined the products formed in the reaction of ClO_2 with selected amino acids as model compounds that can be present in natural waters. The reaction of tryptophane, histidine and tyrosine (10 ppm each) with ClO_2 were studied at molar ratios ranging from 0.25 to 4 in the presence or absence of oxygen. It was found that in the absence of oxygen adding substoichiometric amounts of ClO_2 creates products that are structurally similar to the starting amino acids. Through a series of cascade reactions the initial product distribution gradually evolves toward simple, small carbon chain products that are far from the starting amino acid. The reaction product distribution revealed that chlorine dioxide can attack the electron-rich aromatic moieties as well as the nitrogen atom lone electron pair. Our study is relevant to gain knowledge on the reaction mechanism of ClO_2 with ubiquitous amino acids present in natural waters.

1. Introduction

Among the different chemical agents that can be used as chlorine alternatives for water potabilization, chlorine dioxide is one that has attracted considerable attention [1–9]. The use of chlorine dioxide as a preoxidant instead of chlorine is known to have a beneficial influence of minimizing the trihalomethane (THM) formation following post-chlorination [6,10–17]. Although the origin of this THM reduction when using ClO_2 in pre-oxidation is believed to arise from the lack of ClO_2 tendency to produce chlorination in organic molecules [18].

Aimed at gaining some understanding on the reaction mechanism of chlorine dioxide as a water disinfection agent, herein we have carried out a product study of the reaction of chlorine dioxide with some representative amino acids in water. Among the natural constituents of surface water besides humic and fulvic acids, peptides [19,20] and glycids from plants and microorganisms [21–25] are the main components. Therefore, the positive effect of chlorine dioxide treatment on the reduction of THM content could arise from a specific reactivity of chlorine dioxide with carbohydrates and peptides which is different from that of chlorine. Thus, while most of the studies on the action of ClO_2 have been limited to phenolic structures, some reports [26] have shown that amino acids can give rise to high THM concentrations when reacted with chlorine.

Although there are some old precedents regarding the reactivity of ClO_2 with amine compounds [27,28], it is note worthy that there is a paucity of studies focused on the identification of the chemical structure of the products arising from reaction of organic substrates with chlorine dioxide under conditions and concentrations relevant to potable water treatment [29]. However, systematic studies of the product distribution by reaction of relevant organic compounds with chlorine dioxide could eventually lead to the understanding of the specific way of action of chlorine dioxide with respect to the THM reduction in potable water. Moreover, the actual product distribution could depend on the amount of ClO_2 (substrate to ClO_2 molar ratio) since a cascade of reactions can occur. Therefore, rather than determining the identity of the products resulting from a single ClO_2 dose level, it is more informative to follow the evolution of the product distribution as a function of the ClO_2 concentration. This novel methodology has never been applied to the understanding of ClO_2 pretreatment and can basically answer the question of whether or not the reaction of a given organic compound is catalytic or stoichiometry from the ClO_2 point of view. In addition the role of ambient oxygen on the ClO_2 reaction should be addressed to determine if there is a synergism of the ClO_2 reactivity by oxygen. This point can be simply studied by performing some control experiments in absence of oxygen under inert atmosphere.

2. Experimental

2.1. Generation of chlorine dioxide

Chlorine dioxide was generated by chlorate reduction with sulphuric acid and hydrogen peroxide, according to Eq. (1) [30]. The ClO_2 generation was accomplished by stirring at 60 °C in a flask a

* Corresponding author. Tel.: +34 96 387 7807; fax.: +34 96 387 78 09.
E-mail address: hgarcia@qim.upv.es (H. Garcia).

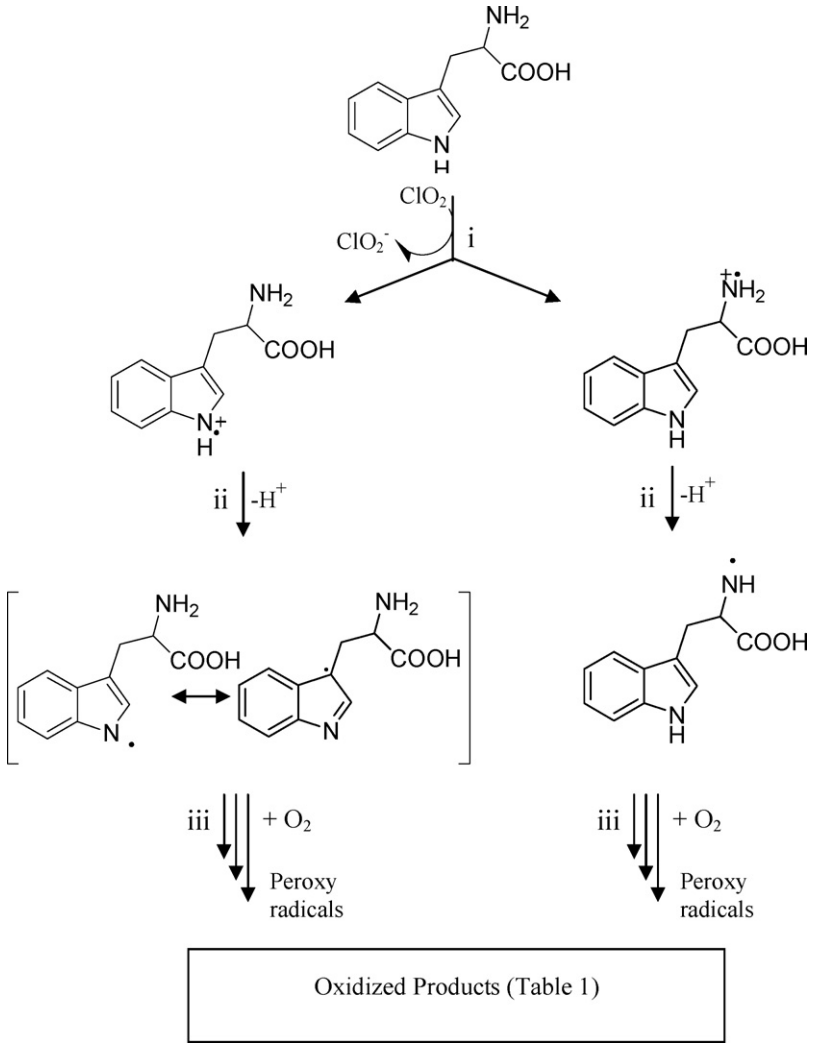
0304-3894/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2008.09.010

mixture of $KClO_3$ (5 g), H_2O_2 (4 mL, 33% in water) and concentrated H_2SO_4 (4.5 mL, 50% in water). The evolved gaseous ClO_2 was collected in water and the resulting concentrated aqueous ClO_2 solution was titrated by determining the optical absorption of the solution at 360 nm (ε_{360} = 1250 cm^{-1} M^{-1}) after buffering the solution pH at 7 (with HCO_3^-, 1 M). ClO_2 is a highly toxic and chemically unstable compound that has to be handled with extreme precaution. Fume hoods and safety gloves and glasses have always to be used. Avoid breathing of ClO_2 vapors. A chlorine dioxide stock solution of 500 ppm was used to dose amino acid solutions in the range of 1–15 ppm ClO_2.

$$2KClO_3 + H_2O_2 + H_2SO_4 \rightarrow 2ClO_2 + O_2 + K_2SO_4 + 2H_2O \quad (1)$$

2.2. General reaction conditions

A previous issue that we considered important when performing the present study is to determine the experimental conditions and the substrate to ClO_2 molar ratio that could later be relevant with respect to those commonly employed in water treatment plants. Obviously all the reactions were performed in water at near ambient temperature under continuous stirring, using amino acid concentrations in the range of 10 ppm and a substrate to ClO_2 molar ratio between 10 and 0.25. In this way, the concentration of amino acid in the synthetic water has been kept to the minimum amount that makes possible product detection while the required ClO_2 to react with this amount of amino acids is only slightly above the concentration that can be used industrially in water potabilization (1.4 ppm as maximum) [31,32]. Also the contact time has to be limited to the usual period occurring during the water treatment process that is typically of a few hours.After titration of ClO_2 at pH 7, experiments have been performed buffered at pH 7.5 with CO_2/HCO_3^- (10 mM) or unbuffered, in which case the pH typically decreased from pH 6 to pH 4 during the course of the reaction. Experiments were conducted in the absence of buffer in order to prevent modification or alteration of the product distribution of each amino acid by the carbonate buffer. A series of reactions were conducted in the presence of oxygen working at the open atmosphere that should permit the formation of oxygenated products. Other series of reactions were carried out using the same substrate concentration (10 ppm) but in the absence of oxygen. Oxygen free solutions were obtained by purging with an Ar stream (45 min) prior to the reaction and conducting the treatment on a sealed vessel. In these cases, the water was not concentrated by rotary evaporation but submitted immediately to lyophilization to ensure the absence of oxygen during the work up. There are some cases in which the solution was coloured and the presence or absence of ClO_2 could not be determined by optical spectroscopy. In these



Scheme 1. Proposed reaction mechanism for the attack of ClO_2 to tryptophane.

cases, the presence of ClO_2 was detected by the positive test using DPD (*N*,*N*′-diethyl-1,4-phenylenediamine) as indicator (ISO 7393-2:1985) [33]. For those reactions in where ClO_2 did not completely react at the final reaction time, the reaction was stopped by addition of sodium thiosulphate (50 mg) until the solution does not give positive test using DPD as indicator.

2.3. Analysis of reaction products

At the final time (24 h) the reaction mixtures were acidified to pH 2 with HCl, concentrated at 40 °C and lyophilized. The residue as suspended in BSTFA + 10% TMCS and the solution stirred at 80 °C for 8 h [34]. The resulting silylated mixture was dissolved in anhydrous acetonitrile, filtered through a 0.45 μm membrane and injected in a gas chromatography GC–MS system (Hewlett Packard HP6890 Chromatograph and mass detector Agilent 5973). The capillary column (30 m) contains crosslinked (5%) phenylmethylsilicone (HP-5MS) as stationary phase. Helium was used as a carrier gas (1.2 mL/min). The injection volume was 1 μL. The injection and detector temperatures were 250 and 280 °C, respectively. The oven temperature programme starts at 50 °C for 3 min, then it increases at a rate of 8 °C/min up to 90 °C, maintains this temperature for 2 min and subsequently rises again at a rate of 15 °C/min up to 280 °C for 10 min [35,36]. Quantification of the reaction products was made by using the internal standard method consisting in the addition of a known amount of nitrobenzene to the solution to be injected. A response factor of 1 was assumed for all the products in the calibration. The absence of buffer makes the analysis of non-volatile products easier since a large quantity of BSTFA is consumed by the buffer. Complete silylation of the reaction products in the presence of buffer requires an enormously large excess of BSTFA since otherwise silylation is not achieved.

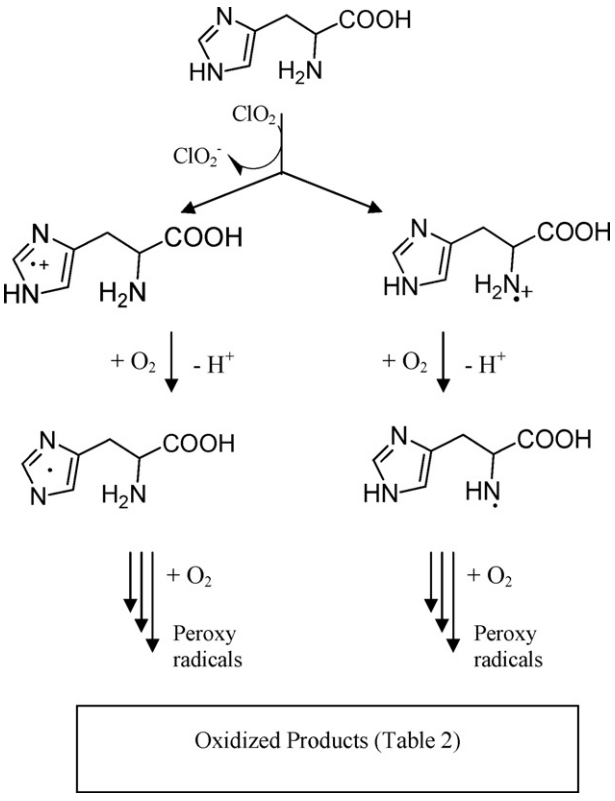
2.4. Compound identification

Product identification was based on the mass spectra of each compound. When the proposed structures were available in the mass spectra databes (NIST 98), the match between the mass spectra and the spectra from the NIST 98 database is given (see Table S5). In some other cases, when commercially available, comparison of the retention time in GC of the proposed structure with that of an authentic standard was made.

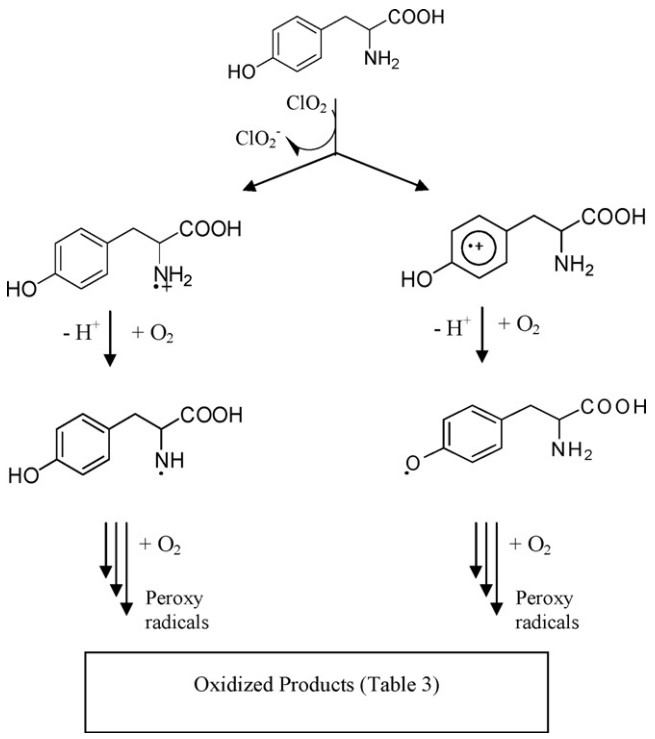
The compounds that had been characterized by comparison of the retention time and MS with authentic standards are listed in Table S1. Furthermore, compounds 5-hydroxy 2,4-imidazolidinedione and *N*-formylanthranilic acid were synthesized by alternative routes (Table S2) [37,38] to compare their retention time and mass spectra of their trimethylsilyl derivatives with the data of the reaction mixture. The identification of the other products was based solely on their mass spectra of their trimethylsilyl derivative and they are also listed in Tables S3, S4 and S5. Supplementary information (Tables S3, S4 and S5) contains the actual mass spectra for each reaction product.

3. Results and discussion

In the present work we have made a product study of the reaction of chlorine dioxide with a series of amino acids that have been earlier reported to react with ClO_2 [39–42]. It is pertinent to comment here that while some kinetic data about the ClO_2 disappearance in the presence of amino acids and peptides [43] constitutes a related precedent to our work, no efforts to disclose the structure of the reaction products was done in these precedents. Schemes 1–3 will summarize our mechanistic proposals. The lack of data related to the chemical structure of the reaction products



Scheme 2. Proposed reaction mechanism for the attack of ClO_2 to histidine.



Scheme 3. Proposed reaction mechanism for the attack of ClO_2 to tyrosine.

with ClO_2 has impeded up to now the understanding of the origin of THM reduction by treating waters with ClO_2 as disinfectant agent instead of chlorine.

3.1. Reaction of ClO_2 with tryptophane

When tryptophane was reacted with excess of ClO_2 (4:1 molar ratio of ClO_2 respect to tryptophane, 10 ppm tryptophane concentration, aerated aqueous solutions, room temperature), the reaction proceeded instantaneously as evidenced by the change in the colour from yellow (characteristic of aqueous ClO_2 solutions) to brown. Our observation agrees with earlier report [43] that measured the ClO_2 disappearance kinetics for the tryptophane/ClO_2 reaction using a fast kinetics stopped-flow set up.

In our case, the analysis of the reaction products has allowed detection of the compounds indicated in Table 1. As can be seen there, when tryptophane is treated with an excess of ClO_2 the most abundant products were oxalic and fumaric acid, accompanied with lesser amounts of 2-aminobenzoic acid, *N*-formylanthranilic acid and 2-(2-oxoindolin-3-ylidene)acetic acid. These products, particularly the two or four carbon atom carboxylic acids, indicate that a cascade of consecutive degradation reactions with extensive carbon–carbon bond breaking has broken tryptophane down into low molecular mass compounds. No other products were observed.

While the previous data indicate the most robust part of the tryptophane structure (the one corresponding to the 2-aminobenzoic moiety) and also that the five-member indol ring is quite reactive and undergoes oxidative ring opening [44], the reaction products are too far from the starting tryptophane to give any indication of the initial sites where chlorine dioxide attacks or to identify some of the primary reaction intermediates with larger number of carbons.

In order to address specifically the initial attack site and also to illustrate in which extent the substrate to ClO_2 molar ratio influences the product distribution, we performed the same reaction between tryptophane and ClO_2 under less ClO_2 excess in the absence of oxygen. The rationale behind this experiment was to stop the reaction cascade at early stages while preventing oxygen from intervening in the degradation pathway.

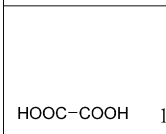
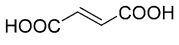
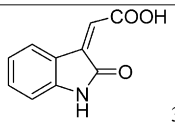
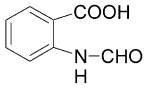
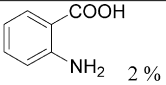
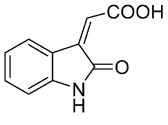
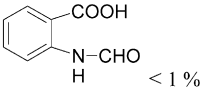
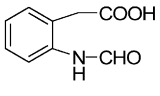
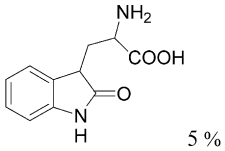
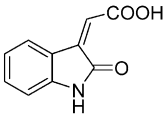
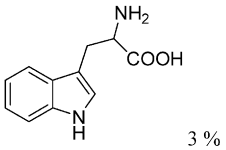
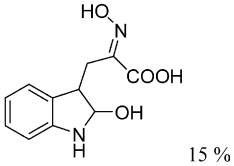
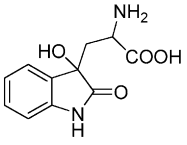
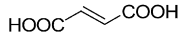
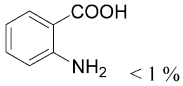
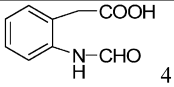
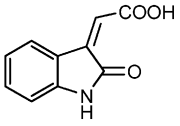
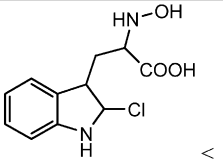
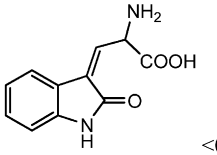
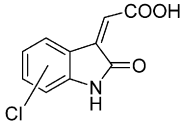
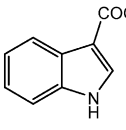
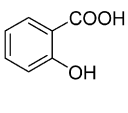
As expected, the product distribution under these conditions changes completely with respect to that previously commented for ClO_2 excess under aerobic conditions. Also in accordance with our expectations the majority of the products still contain most of the carbon skeleton intact or very similar to that of tryptophane.

Upon consideration of the product structures it can be inferred that there are two preferential competing sites at which reactions between ClO_2 and tryptophane can take place (Scheme 1). One of them is the amino acid nitrogen atom forming hydroxylamines, oximes and imines. In the chemistry of organic nitrogenated compounds oxidation to hydroxyl imines, oximes and imines is a well-known chemistry [45]. Although no evidence based on product characterization was obtained, it is very likely that further oxidation at this position will lead eventually to the loss of the lateral chain with disconnection between the indol and the α-amino acid moieties. Oxidative C—C bond breaking in the α-positions to heteroatoms is also a well-known process [45].

On the other hand, ClO_2 also attacks to the 2 and 3 positions of the indol ring producing initially hydroxylation of a ring with subsequent formation of the carbonyl group that eventually promotes ring opening. Indol chemistry has been subject of extensive studies [46].

A reasonable degradation route to account for the products observed is proposed in Scheme 1. According to this scheme that is compatible with thermodynamic data based on known redox potential of tryptophane and ClO_2, the products formed in the early degradation events will arise from single electron transfer. Single electron donation from electron-rich organic molecules is a very general process for aromatic amines and heterocycles that can lead to degradation [47]. In this process, ClO_2 will be converted into chlorite while a highly reactive tryptophane radical cation will be formed (Scheme 1).

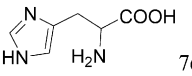
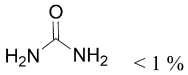
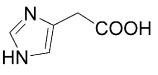
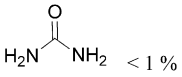
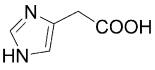
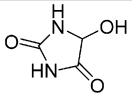
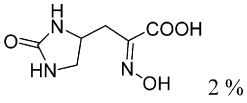
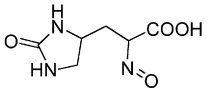
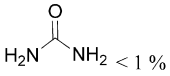
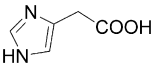
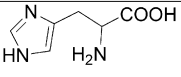
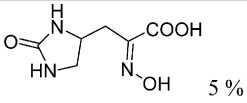
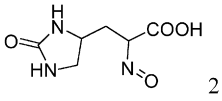
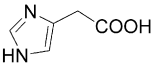
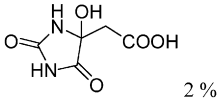
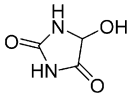
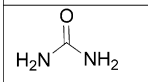
Table 1
Product distribution observed for the reaction of ClO_2 with tryptophane, at 20 °C, under argon or oxygen atmosphere using several reagent molar ratios.

Tryptophane / ClO_2 Molar Ratio 0.25, under oxygen atmosphere, pH from 6 to 4		
 10 %	 1 %	 3 %
 3 %	 2 %	
Tryptophane / ClO_2 Molar Ratio 0.5, under oxygen atmosphere, pH from6 to 4		
 4 %	 < 1 %	 1 %,
Tryptophane / ClO_2 Molar Ratio 1, under argon atmosphere, pH from 6 to 4		
 5 % Mixture of stereoisomers	 3 %	 3 %
 15 % Mixture of stereoisomers	 4 %	
Tryptophane / ClO_2 Molar Ratio 0.5, under oxygen atmosphere, pH buffered 7.5		
 2 %	 < 1 %	 4 %
 < 0.5 %	 < 0.5%	 <0.5%
 < 0.5 %	 < 0.5 %	 < 0.5 %

The product percentage has been estimated using nitrobenzene as external GC standard and is given with respect to the initial moles of tryptophane.

Cyclic voltammetry of tryptophane in aqueous solution shows an oxidation potential around +1.0 V vs NHE [48] and therefore it should be easily oxidized by ClO_2 [49] (Eox = 1.27 V vs NHE). Two possible sites of tryptophane can give the electron to ClO_2 either the lone pair of amino acid nitrogen atom or from the electron-rich five member ring heterocycle of the indol structure. After the initial electron transfer, tryptophane radical cation can evolve giving a proton and forming the corresponding radical that would couple with ClO_2. In this regard we should recall the radical nature of ClO_2. Thus, ClO_2 will attack to the tryptophane derived radical

Table 2
Product distribution observed for the reaction of ClO_2 with histidine, at 20 °C, under argon or oxygen atmosphere using several reagent molar ratios.

Histidine / ClO_2 Molar Ratio 10 , under oxygen atmosphere, pH from 6 to 4		
 76 %	 < 1 %	
Histidine / ClO_2 Molar Ratio 1, under argon atmosphere, pH from 6 to 4		
 10 %	 < 1 %	
Histidine / ClO_2 Molar Ratio 1, under oxygen atmosphere, pH buffered 7.5		
HOOC–COOH < 1 %	 3 %	 < 1 %
 2 %	 1 %	 < 1 %
Histidine / ClO_2 Molar Ratio 1, under argon atmosphere, pH buffered 7.5		
HOOC–COOH 1 %	 22 %	 17 %
 5 %	 2 %	
Histidine / ClO_2 Molar Ratio 0.33, under argon atmosphere, pH from 6 to 4		
 41 %	 2 %	 1 %
 < 1 %		

The product percentage has been estimated using nitrobenzene as external GC standard and is given with respect to the initial moles of histidine.

forming a covalent bond giving rise to a chlorite ester which would hydrolyze to a tryptophane hydroxy derivative. Also at the stages of radical cation or radical, the species can react with dissolved oxygen when the reaction is carried out under aerobic conditions. Thus, ClO_2 shows as preferential attack sites either at the amino acid nitrogen or at C-2 and C-3 of the indol ring (Scheme 1). Then, in the absence of oxygen, if an excess of ClO_2 is present, these primary products will be unstable and will continue their way to further degradation by consecutive reactions with ClO_2 (see Scheme 1).

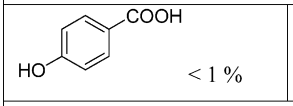
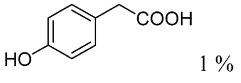
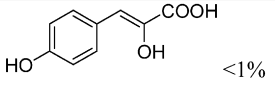
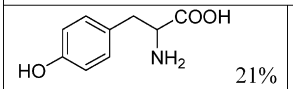
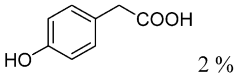
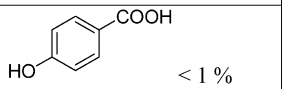
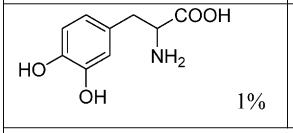
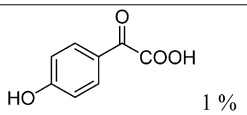
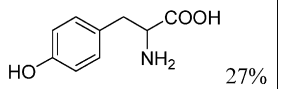
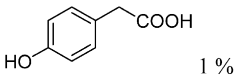
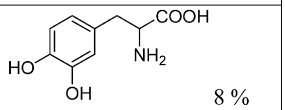
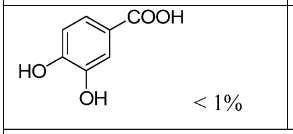
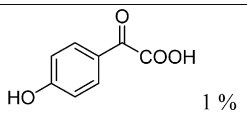
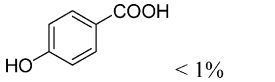
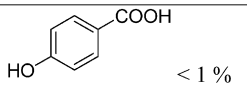
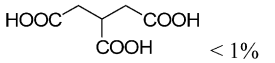
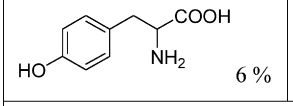
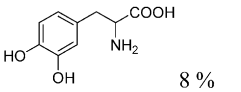
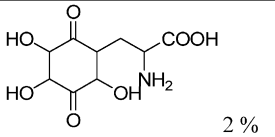
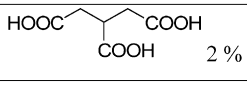
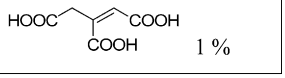
Different pathways are possible depending on the position of the second and subsequent attacks (Scheme 1). When the attack has occurred initially at the amino acid nitrogen, the reaction route probably continues with the formation of multiple carbon–nitrogen bonds and decarboxylation [2-(hydroxyimino)-3(2-hydroxy-indolin-3-yl)propanoic acid, 3-(2-chloroindolin-3-yl)-2-(hydroxy-amino)propanoic acid, 2-(2-oxoindolin-3-ylidene)acetic acid, indole-3-carboxylic acid]. When the initial attack was at the indol ring further hydroxylation and ketone formation would occur leading eventually to the heterocyclic ring aperture [2-amino-3-(3-hydroxy-2-oxoindolin-3-yl)propanoic acid, *N*-formylanthranilic acid]. According to the product distribution observed for the high substrate to ClO_2 molar ratios it seems that attack to the indol ring is more favourable giving higher product yields than attack to the amino acid nitrogen [46]. The latter will proceed leading to products with a few carbon atoms.

In summary according to our data, ClO_2 initiates the attack to tryptophane by single electron abstraction and subsequent oxidative radical coupling processes. Oxygen is not needed in the initial steps but, if present in the medium, it will intervene intercepting the radicals and given oxygenated products.

3.2. Reaction of histidine with ClO_2

The previous conceptual framework to understand tryptophane degradation also applies in part for histidine degradation by ClO_2 (Scheme 2). Thus, under conditions in which there is an excess of ClO_2 with respect histidine, and working under aerobic conditions, extensive degradation steps occurs leading to one or three carbon carboxylic acids as indicated in Table 2. Histidine degradation under these conditions is not a chain reaction since when histidine/ClO_2 molar ratio is 10 most of histidine remains unaltered even in the presence of oxygen. Nevertheless, the role of oxygen promoting decomposition after the initial stoichiometric attack of ClO_2 is also manifested by the fact that treating histidine with ClO_2 under argon shows a different product distribution pattern, wherein the primary products arise from the preferential attack of ClO_2 to the amino acid nitrogen atom leading in the case of histidine to high chemical

Table 3
Product distribution observed for the reaction of ClO_2 with tyrosine, at 20 °C, under argon or oxygen atmosphere using several reagent molar ratios.

Tyrosine / ClO_2 Molar Ratio Ratio 0.25, under oxygen atmosphere, pH from 6 to 4		
HOOC–COOH 6 %		
Tyrosine / ClO_2 Molar Ratio 0.4, under oxygen atmosphere, pH from 6 to 4		
 < 1 %	 1 %	 <1%
Tyrosine / ClO_2 Molar Ratio 1, under oxygen atmosphere, pH from 6 to 4		
 21%	 2 %	 < 1 %
 1%	 1 %	
Tyrosine / ClO_2 Molar Ratio 1, under argon atmosphere, pH from 6 to 4		
 27%	 1 %	 8 %
 < 1%	 1 %	 < 1%
Tyrosine / ClO_2 Molar Ratio 0.5, under oxygen atmosphere, pH buffered 7.5		
 4 %	 < 1 %	 < 1%
 6 %	 8 %	 2 %
Tyrosine / ClO_2 Molar Ratio 0.25, under oxygen atmosphere, pH buffered 7.5		
HOOC–COOH 10 %	 2 %	 1 %

The product percentage has been estimated using nitrobenzene as external GC standard and is given with respect to the initial moles of tyrosine.

yields of the corresponding 4-imidazolyl acetic acid. As in the case of tryptophane, this primary compound is again not stable and, if an excess of ClO_2 is available, hydroxylated heterocyclic compounds start to appear leading eventually to the cleavage of the histidine lateral chain and the heterocyclic ring opening. Table 2 contains a summary of the products characterized as a function of the ClO_2 molar ratio and the presence or absence of oxygen.

3.3. Reaction of ClO_2 with tyrosine

The same methodology, i.e., working at different substrate to ClO_2 molar ratio either in presence or absence of oxygen, was also applied to understand the degradation of tyrosine and the resulting reaction products. The product distribution characterized upon the treatment of tyrosine with ClO_2 is shown in Table 3. As on the previous cases, stoichiometric amounts of ClO_2 in the absence of oxygen lead to products that are structurally closely related to the starting tyrosine.

Recently the ClO_2 oxidation of tyrosine in presence of oxygen using a substoichiometric amount of ClO_2 has been studied [29] and the formation of 3-(3,4-dihydroxyphenyl)-L-alanin (L-DOPA) has been observed by UV spectroscopy. In contrast, in our case, excess of ClO_2 in the presence of oxygen leads to short-chain, highly functionalized carboxylic acids very far from the starting tyrosine. This again indicates that ambient oxygen is intercepting radical species leading to massive degradation of the initial structure. By combining the product distribution of this series of reactions under different conditions, a more complete understanding of the degradation pathways was obtained. Based on Table 3 a degradation route can be proposed as indicated in Scheme 3. Common with the previous examples is that the initial proposed step consists of a single electron oxidation of tyrosine, followed by a series of radical couplings and decarboxylation of the phenolic lateral chain. In this way, phenolic carboxylic acids with one or two aliphatic carbon atoms are formed. Also, hydroxylation of the aromatic ring forming hydroquinone derivatives is competitively occurring and eventually will lead to the benzene ring rupture and formation of mono and dicar-

boxylic acids. Again hydroxylation can take place by ClO_2 coupling with a carbon centered radical and hydrolysis of the corresponding chlorite ester or by the interception and trapping by oxygen of the carbon centered radicals.

4. Conclusions

In the present work we have shown that the product distribution for the reaction of a compound with an excess of ClO_2 in the presence of oxygen is not enough to obtain sufficient conclusive information about the operating degradation pathways. In fact, the product distribution changes drastically depending on whether substoichiometric or excess amounts of ClO_2 are used and also on the presence or absence of oxygen. Also we have shown that appropriate characterization of the reaction products requires the adequate derivatization of polyhydroxylic and carboxylic acids. By applying a systematic methodology, consisting of increasing the ClO_2 molar ratio and performing the reaction in the absence or presence of oxygen to the three amino acids studied, we have reached the conclusion that ClO_2 attack initiates at the amino acid nitrogen atom or at electron donor aromatic substructures. The initial primary products are unstable under the reaction conditions and continue the degradation mainly by a cascade of hydroxylation, carbonyl formation, decarboxylation and ring opening steps. Given the current and potential importance of ClO_2 treatment for water potabilization our study is relevant to gain insight into the mechanisms of THM formation potential reduction by ClO_2 as compared with conventional chlorination treatment. This type of studies can be of relevance to understand the influence of ClO_2 pretreatment on subsequent THM evolution.

Acknowledgement

Financial support by the Spanish Ministry of Education (CTQ06-06859) is gratefully acknowledged. SN thanks the Universidad Politecnica de Valencia for a fellowship (Cantera programme).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhazmat.2008.09.010.

References

[1] S. Sussman, W.J. Ward, Chlorine dioxide is an attractive water treatment alternative, Water & Sewage Works (1979) 120–121.
[2] G.W. Miller, R.G. Rice, C.M. Robson, R.L. Scullin, W. Kuhn, An Assessment of Ozone and Chlorine Dioxide Technologies for Treatment of Municipal Water Supplies, Public Technol., Inc., Washington, DC, USA, 1978, 81 pp.
[3] AWWA Research Foundation & KIWA, Use of alternative disinfectants, Chlorination By-Products: Production and Control (1986) 174–188.
[4] E.M. Aieta, J.D. Berg, A view of chlorine dioxide in drinking water treatment, Journal of AWWA 78 (1986) 62–73.
[5] L. Helin, B. Ling, Application of chlorine dioxide in water treatment, Water Treatment Technology, China 15 (1987) 174–178.
[6] A.G. Myer, Evaluating alternative disinfectants for THM control in small systems, Journal of AWWA 82 (1990) 77–84.
[7] G.C. White, The Handbook of Chlorination and Alternative Disinfectants, 3rd ed., Van Nostrand Reinhold, New York, 1992, pp.150–151.
[8] N. Narkis, A. Katz, F. Orshansky, Y. Kott, Y. Friedland, Disinfection of effluents by combinations of chlorine dioxide and chlorine, Water Science Technology 31 (1995) 105–114.
[9] K.M. Sutton, R. Elefritz, J. Milligan, THM control in wastewater effluent with chlorine dioxide as a supplementary oxidant, in: Disinfection 2002, Health and Safety Achieved through Disinfection, Conference Proceedings, St. Petersburg, FL, United States, February 17–20, 2002, pp. 152–165.
[10] J.M. Symons, O. Love, Thomas Jr., C. Keith, Comparison of practical alternative treatment schemes for reduction of trihalomethanes in drinking water, in: Ozone/Chlorine Dioxide Oxid. Prod. Org. Mater., Proc. Conf., 1978, pp. 443–455.
[11] W. Benjamin, J.R. Lukins, H. Mark, Using chlorine dioxide for trihalomethane control, American Water Works Association 78 (1986) 88–93.
[12] N.J.D. Graham, G. Reynolds, D. Buckley, Laboratory simulation of disinfection regimes for trihalomethane control, Journal of the Institution of Water and Environmental Management 3 (1989) 604–611.
[13] R. McVeigh James, G. Lee Ramon, D.L. Kelleher, Chlorine dioxide use in pretreatment for control of trihalomethane generation, in: Proceedings Annual Conference, American Water Works Association, 1995, pp. 825–829.
[14] S.W. Krasner, Chlorine dioxide treatment of drinking water: oxidant demand and byproduct formation, in: 38th Western Regional Meeting of the American Chemical Society, Long Beach, CA, United States, October 15–18, 2003, p. 122 (Abstracts).
[15] B.W. Long, R.F. Miller, A.A. Rosenblatt, Pilot study: the use of high-purity, chlorine-free chlorine dioxide to minimize trihalomethane formation, Chemical Oxidation 6 (1997) 126–133.
[16] G. Gordon, B. Bubnis, Chlorine dioxide chemistry issues, in: Chlorine Dioxide: Drinking Water, Process Water and Wastewater Issues, Symposium Proceedings, 3rd, New Orleans, September 14–15, 1995, 1996, pp. 1–15.
[17] B.W. Lykins, M.H. Griese, Using chlorine dioxide for trihalomethane control, American Water Works Association 78 (1986) 88–93.
[18] J. Hoigné, H. Bader, Kinetics of reactions of chlorine dioxide (OClO) in water-I. Rate constants for inorganic and organic compounds, Water Research 28 (1994) 45–55.
[19] C. Le Cloirec, P. Le Cloirec, M. Elmghari, J. Morvan, G. Martin, Concentration and analysis of numerous nitrogenous organic substances in natural waters, International Journal of Environmental Analytical Chemistry 14 (1983) 127–145.
[20] M.H. Briggs, The presence of free sugars, peptides, and amino acids in filtered lake waters, Life Science 1 (1962) 377–380.
[21] J. Buffle, Complexation Reactions in Aquatic Systems-An Analytical Approach, Ellis Horwood Limited, England, 1990.
[22] K.W.W. Chin-Chang Hung, Peter H. Santschi, A seasonal survey of carbohydrates and uronic acids in the Trinity River, Texas, Organic Geochemistry 36 (2005) 463–474.
[23] A. Mannino, H.R. Harvey, Biochemical composition of particles and dissolved organic matter along an estuarine gradient: sources and implications for DOM reactivity, Limnology and Oceanography 45 (2000) 775–788.
[24] P.A. Meyers, Reaction mechanisms in environmental organic chemistry by R.A. Larson and E.J. Weber, Organic Geochemistry 23 (1995) 95.
[25] E.M. Thurman, in: M. Nijhof, D.W. Junk (Eds.) Organic Geochemistry of Natural Waters (1985).
[26] B. Legube, L. Hureiki, J.P. Croué, Chlorination studies of free and combined amino acids, Water Research 28 (1994) 2521–2531.
[27] M. Doré, Chimie des Oxidants et Traitement des Eaux, Technique et Documentation-Lavoisier, 1989.
[28] H. David, A. Rosenblatt, Hull Larry, C. Donald, DeLuca, R.G. Davis George Thomas, H.K. Weglein, R. Williams, Oxidations of amines. 11. Substituent effects in chlorine dioxide oxidations, Journal of the American Chemical Society 89 (1967) 5.
[29] M.J.G. Napolitano, J. Brandon, J.S. Nicoson, D.W. Margerum, Chlorine dioxide oxidations of tyrosine, *N*-acetyltyrosine, and dopa, Chemical Research in Toxicology 18 (2005) 501–508.
[30] M. Burke, J. Tenney, B. Indu, M.F. Hoq, S. Carr, W.R. Ernst, Kinetics of hydrogen peroxide-chlorate reaction in the formation of chlorine dioxide, Industrial & Engineering Chemistry Research 32 (1993) 1449–1456.
[31] USEPA, Alternative disinfectants and oxidants guidance manual, EPA-815-R-99-014, 1999.
[32] D.J. Gates, The Chlorine Dioxide Handbook (Water Disinfection Series), American Water Works Association, 1998.
[33] APHA, Mehod 4500-ClO2-D, Standard methods for examinattion of water and wastewater, 18 ed., 1992.
[34] S. Navalon, M. Alvaro, H. Garcia, Reaction of chlorine dioxide with emergent water pollutants: product study of the reaction of three b-lactam antibiotics with ClO_2, Water Research 42 (2008) 1935–1942.
[35] W.V. Ligon, H. Grade, Techniques for postcolumn derivatization in gas chromatography/mass spectrometry, Analytical Chemistry 63 (1991) 255–261.
[36] D. Li, J. Park, J.R. Oh, Silyl derivatization of alkylphenols, chlorophenols, and bisphenol A for simultaneous GC/MS determination, Analytical Chemistry 73 (2001) 3089–3095.
[37] M. Chakrabarty, K. Shampa, Y. Harigaya, Y. Konda, Neat formic acid: an excellent *N*-formylating agent for carbazoles, 3-alkylindoles, diphenylamine and moderately weak nucleophilic anilines, Synthetic Communications 30 (2000) 187–200.
[38] M.T.S. Yamada, Preparation of 5-hydroxyhydantoin, European Patent Application (1991).
[39] K. Taymaz, D.T. Williams, F.F. Benoit, Reactions of aqueous chlorine dioxide with amino acids found in water, Bulletin of Environmental Contamination and Toxicology 23 (1979) 456–463.
[40] I. Noss Charles, H. Dennis William, P. Olivieri Vicent, Reactivity of chlorine dioxide with nucleic acids and proteins, Water Chlorination: Environmental Impact and Health Effects 4 (1983) 1077–1086.
[41] H.K. Tan, W.B. Wheeler, C.I. Wei, Reaction of chlorine dioxide with amino acids and peptides: kinetics and mutagenicity studies, Mutation Research 188 (1987) 259–266.
[42] A.C. Sen, J. Owusu-Yaw, W.B. Wheeler, C.I. Wei, Reactions of aqueous chlorine and chlorine dioxide with tryptophan, *N*-methyltryptophan, and 3-indolelactic acid: kinetic and mutagenicity studies, Journal of Food Science 54 (1989) 1057–1060.

[43] H. Tan, A.C. Sen, W.B. Wheeler, J.A. Cornell, C.I. Wei, A kinetic study of the reaction of aqueous chlorine and chlorine dioxide with amino acids, peptides and proteins, Journal of Food Science 52 (1987) 1706–1711.
[44] R.J. Sundberg, The chemistry of indoles, in: A.T. Blomquist (Ed.), Organic Chemistry, a Series of Monographs, Academic Press, New York and London, 1970.
[45] Jerry March, Michael B. Smith, March's advanced organic chemistry, Reactions, Mechanisms, and Structure (6th ed.) (2007).
[46] A.R. Katrizky, Advances in Heterocyclic Chemistry 83. (2002).
[47] J.K. Whitesell, M.A. Fox, Core Organic Chemistry, Jones and Bartlett, Boston, 1997.
[48] A. Harriman, Further comments on the redox potentials of tryptophan and tyrosine, Journal of Physical Chemistry 91 (1987) 6102.
[49] E. Metcalf, Inc., Wastewater Engineering Treatment and Reuse, McGraw-Hill, New York, 2003.