Comparison of electrochemical method with ozonation, chlorination and monochloramination in drinking water disinfection

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ABSTRACT

Electrochemical process in chloride-free electrolytes was proved to be powerful in disinfection due to the strong oxidants produced in the electrolysis and no formation of disinfection byproducts (DBPs). In this study, disinfection experiments were conducted by electrochemical treatment compared with ordinary and advanced methods (ozonation, chlorination and monochloramination), with Escherichia coli (E. coli) K-12, Staphylococcus aureus (S. aureus) A106, Bacillus subtilis (BST) and an isolated Bacillus as the representative microorganisms. Firstly, factor tests were performed on E. coli to obtain the optimal conditions of the four disinfection procedures. At their respective optimal condition, CT (concentration of disinfectant × contact time) value of a 4-log E. coli inactivation was 33.5, 1440, 1575, 1674 mg min L−1 for electrochemical process, ozonation, chlorination and monochloramination, respectively. It was demonstrated that the disinfection availability was in the following order: electrochemical process > ozonation > chlorination > monochloramination, which could be attributed to the hydroxyl radical generated in the electrolysis, with strong oxidizing ability and non-selectivity compared with the other three disinfectants. Moreover, the disinfection efficacy of the four disinfection procedures was compared for four different bacteria. It was found that the disinfection efficacy was similar for the selected four bacteria in electrochemical process, while in the other three treatments inactivation of the two Bacillus was much slower than E. coli and S. aureus. As a result, the non-selectivity of electrochemical disinfection with BDD anode to different kinds of microorganisms was further proved, which was primarily controlled by the hydroxyl radicals existed in the free state. For each bacterium, the order of disinfection availability of the four processes was consistent. Finally, scanning electron microscopy (SEM) was implemented to observe the cell morphology. It was shown that cell surface damage was more obvious in electrochemical system with strong oxidants compared with that after ozone treatment, while the integrity of cells were not affected in weak oxidizing chlorine and monochloramine.

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1. Introduction

Disinfection is an essential drinking water treatment step to keep consumers away from infectious diseases by pathogenic microorganisms. Ordinary and advanced disinfection methods include chlorine, monochloramine, chlorite, ozone, hydrogen peroxide, UV and electrochemical treatment. Chlorination is the most historical methods to present; however, disinfection byproducts (DBPs) produced from chlorination has attracted more and more concerns [1]. As a substituent technology, monochloramine could maintain the original disinfection properties and lower the formation of DBPs [2]. Ozone is a strong oxidant and could inactivate many kinds of microorganisms effectively [3] with the limited factor of ozone production [4]. Besides, electrochemical processes in both chlorine and chloride-free electrolytes were proved to be highly-efficient in disinfection, even for Cryptosporidium parvum oocysts and Clostridium perfringens spores which were resistant to chlorine [5]. It had attracted more and more attention due to the strong oxidants produced in the electrolysis. Inactivation efficiencies were especially excellent with the boron-doped diamond (BDD) anode, whose unique quality had already shown in organic pollutants degradation [6].

It is important to understand the mechanisms of different inactivation methods, which would be helpful to identify rate-limiting steps in the disinfection and to develop more effective strategies in practical disinfection application. Comparison of different disinfection processes have been reported in some previous research. Waldemer et al. [7] reported that monochloramine is an oxidant with relatively low reactivity towards most chemical functional groups. Its disinfection ability was much weaker than chlorine [8]. Ozone was proved to be superior to chlorine and monochloramine in Cryptosporidium parvum oocysts inactivation [3,9] as well as

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Bacillus subtilis (BST) spores [10,11]. Cho et al. [12] tested disinfection efficiencies of ozone and free chlorine accompanied with the detection of protein release, lipid peroxidation and change in cell permeability, taking E. coli as the representative microorganism. It showed that ozone caused the greatest level of surface damage while the least by free chlorine. Ozone has a stronger oxidizing ability to react with the organics on the cell wall before penetrating into the cell plasma, which caused severe surface damage; for chlorine with a weaker oxidize ability, reaction with the organics on the cell wall was limited and inactivation of cells was realized through its reaction with intracellular components [12]. There are many indications that electrolyzed water has a higher disinfecting activity compared to normal commercially available hypochlorite solutions [13] but the comparison is difficult, due to the adjustment of equal starting conditions such as initial oxidant concentration. For example, Li et al. [14] and Diao et al. [15] took E. coli as the indicator microorganism in the electrochemical disinfection, comparing it with ozonation and chlorination, and SEM observations after different means of disinfection also suggested that bacteria in the electrochemical treatment with chloride electrolyte were likely killed by the chemical products with germicidal powers similar to that of ozone and much stronger than that of chlorine. However, the assurance of the same conditions for comparison was not very clear. Besides, Bergmann et al. [16] indicated that electrolyzed water (50 mg L\(^{-1}\) Cl\(^-\)) had a higher lethal efficiency than Ca(ClO\(_2\)) of the same measured active chlorine concentration. Anyhow in the author’s opinion, it is improper to compare them not considering all oxidative species in the system. Perhaps difference in disinfection efficiency originated from special characters of the species in various methods.

E. coli is a widely used indicator microorganism for bacteriologic water quality. However, inactivation of E. coli cannot represent automatically for all kinds of microorganisms’ elimination. Nakajima et al. [17] and Delaedd et al. [18] showed that a complete eradication of a bacterial suspension after 5 min of electrolysis was obtained with 20 mA in the case of E. coli, but with 30 mA when treating Legionella. Pneumophila (L. pneumophila). E. coli seems therefore more vulnerable to electrochemical disinfection compared with L. pneumophila. Bergmann et al. [16] tested three microorganisms for chlorination, ozonation and electrochemical disinfection. And the result indicated E. coli cells were more sensitive than BST and Saccharomyces cerevisiae Kolin cells. Moreover, it is reported that Gram-positive Staphylococcus aureus (S. aureus) exhibits stronger drug-resistance than Gram-negative colon Bacillus due to their different peptidoglycan structures [19]. Tyrrell et al. [20] tested five indigenous populations (including fecal coliforms, enterococci, Clostridium perfringens, male-specific bacteriophage and somatic coliphage) in secondary sewage effluents using chlorine and ozone. Inactivation efficiency differed significantly with each other and it is demonstrated that only one bacterium indicator, such as the fecal coliform, is inadequate for predicting microorganism responses in the disinfection treatments.

The reactive oxygen species (ROS, mainly including \( \bullet \)OH) produced in electrolysis was predicted to play a significant role in electrochemical chloride-free disinfection [13,14]. However, comparison of electrochemical process with other disinfection methods aiming at different kinds of bacteria was hardly studied. Whether the disinfection efficacy in electrochemical system would be still superb compared with other disinfection for different kinds of microorganisms, will be powerful evidence to illustrate and prove the unique role of \( \bullet \)OH in mechanism of electrolysis.

Consequently, four bacteria (E. coli, S. aureus, BST, an isolated Bacillus) were used as the indicator microorganisms in this paper, in comparison of four disinfection processes including chlorination, monochloramination, ozonation and electrochemical treatment. Mechanism was put forward through the difference in inactivation efficiencies as well as the SEM analysis for the four bacteria. The special role of \( \bullet \)OH existed in the BDD anode system as a free state was verified in electrochemical chloride-free disinfection.

2. Experimental

2.1. Solution composition

All disinfection solutions were prepared with deionized Milli-Q water (Millipore). The base electrolyte was constituted with aqueous solutions of 0.2 M Na\(_2\)SO\(_4\) in the electrochemical disinfection. Chlorine concentrated solution (0.1 g L\(^{-1}\)) was prepared in deionised water with sodium hypochlorite on the day of use. Fresh monochloramine stock solutions were prepared daily for experiments according to Dow et al. [11]. Ozone was produced with a Fischer 502 ozone generator and a stock solution (>50 mg L\(^{-1}\)) was prepared by sparging ozone-containing oxygen through Milli-Q water that was cooled in an ice bath [21].

Desired initial concentration (0.1–5 mg L\(^{-1}\) for chlorine, 0.5–5 mg L\(^{-1}\) for monochloramine and 0.5–5 mg L\(^{-1}\) for ozone) was obtained by taking a certain volume of the stock solution into sterilized deionised water. The initial pH of all the experiments was adjusted to 7.1, with 4 mL phosphate buffer solution (pH = 7.1) supplemented. The pH value was almost unchanged during the runs.

2.2. Experimental apparatus

Electrochemical disinfection was carried out at room temperature (20°C) in a 400 mL beaker under galvanostatic conditions. BDD with an exposed geometric area of 1 cm\(^2\) (bought from CON-DIAS GmbH, Germany) was used as the anode and stainless steel as the cathode. The current density in this study was 20 mA cm\(^{-2}\).

Disinfection experiments of ozonation, chlorination and monochloramination were all conducted in a 500 mL lidded Erlenmeyer flask which was wrapped with silver paper to keep the reaction solution in dark.

The starting systems with added microorganisms were under agitation by a magnetic stir bar, with a total volume of 200 mL in all disinfection experiments.

2.3. Disinfection experiments

The following four microorganisms were used in this study: E. coli K-12, S. aureus A106, BST obtained from Dr. Yao Maosheng (at college of environmental sciences and engineering, Peking University, China) and another Bacillus isolated from Long River in Hebei Province. There was 10 g peptone, 9 g NaCl (>75 g NaCl for S. aureus), 3 g beef extract and 18 g agar in 1000 mL nutrient medium. For preculture, a single colony was inoculated in 100 mL of sterile nutrient broth and grown at 35°C for 24 h (72 h for S. aureus) with 130 revolutions per minute (rpm) agitation to reach its stationary phase as microorganisms of logarithmic state behave more sensitive in electrolysis. A certain amount of the nutrient broth was taken out and centrifugated in a 7 mL conical tube at 10,000 rpm (+5°C) for 5 min, washed with 10 mL sterile deionized water prior to each disinfection experiment. Then cell suspensions were diluted with sterile solvents to the required initial cell density corresponding to 10\(^5\) colony forming units per millilitres (CFU mL\(^{-1}\)) for use in the experiments. The prepared cell stock was stirred for at least 20 min before use.

After taking the sample at timed intervals the reaction was immediately terminated with adding excess sodium thiosulfate solution (10 mM) during the experimental runs. Glasswares used in the disinfection experiments were all washed with deionized
water and then autoclaved at 120 °C for 30 min. All the disinfection experiments were performed in triplicate at least, and average results were presented in the figures, with error bars displaying the standard deviation (SD).

2.4. Analytical methods

The concentration of survival microorganisms was determined by plating and counting colonies according to the procedures reported in a previous research [22]. Each sample was cultured in triplicate to ensure the accuracy. Survival data was expressed as log (N/N0), where N0 is the number of initial colonies and N is the number of colonies after electrochemical disinfection. And the concentration of free chlorine and monochloramine were determined by N-diethyl-p-phenylenediamine (DPD) colorimetric method according to APHA [23]. The dissolved ozone was detected by the indigo colorimetric method [21].

The high-resolution environmental scanning electron microscopy (ESEM) (FEI Quanta 200F) was employed to examine the morphology of four bacteria cells before and after the disinfection treatment. Untreated bacterial cells was considered as the control sample, and completely disinfected bacterial cells (including electrochemical, chlorination, monochloramination and ozonation disinfection) was used as the sample after the different disinfection processes. Firstly, the 100 mL solvents containing bacteria cells were concentrated by centrifugation (5810R, Eppendorf) at 5000 rpm for 15 min. A faster speed had been avoided in case of the cell breakage. Then the supernatant was discarded and the cells were resuspended into 1 mL sterilized deionized water. Take one drop of the suspension onto a small piece of single crystal silicon chip. Finally it could be viewed under ESEM after it dried physically in the air.

3. Results and discussion

3.1. Optimization of the four disinfection processes

The way to compare different disinfection processes under a certain amount of total oxidation concentration is not thought to be proper, due to the kinds of oxidants in different disinfection processes are different and thus it is not convincing only based on the concentration value. Thus, experiment design was carried on to find the optimum reaction parameters in order to put on the comparison.

Electrochemical disinfection of E. coli has been performed under different current density (5–40 mA cm⁻²), electrolyte substrates (Na₂SO₄, NaH₂PO₄ and NaNO₃) and electrolyte concentration (0.005–0.2 M), which had been reported in a previous research [22]. The optimal condition for E. coli inactivation in electrochemical system is at a current density of 20 mA cm⁻² in 0.2 M Na₂SO₄ electrolyte.

Fig. 1(a) shows the influence of ozone concentration on the trends of E. coli inactivation efficiency from 0.5 mg L⁻¹ to 5 mg L⁻¹ in 10-min process, as it is reported that problem of ozone decomposition would occur with a longer contact time [24]. With increasing ozone concentration, the time needed for an equivalent E. coli inactivation was shortened gradually. As presented in Fig. 1(a), when the ozone concentration was raised every 1 mg L⁻¹, log inactivation of E. coli increased most obviously at a concentration of 3 mg L⁻¹. As a result, an ozone concentration of 3 mg L⁻¹ was the optimal one, considering the cost and the inactivation efficiency comprehensively.

Similarly, chlorine and monochloramine disinfection experiments were conducted under a series concentration, 0.1–5 mg L⁻¹ for chlorine and 0.5–5 mg L⁻¹ for chloramines, respectively, shown in Fig. 1(b) and (c). Finally the optimal concentration in disinfection process was determined to be 0.5 mg L⁻¹ for chlorine and 2.5 mg L⁻¹ for monochloramine.

It can be observed that E. coli was inactivated much faster in the initial phase of chlorine, monochloramine and ozone processes, however, the plots became gradually smooth later. Comparatively speaking, electrochemical inactivation kept a uniform trend in the whole process. It is known that •OH, which was vital to the bacteria inactivation, was consecutively produced in the electrolysis, while disinfectants concentration was highest in the beginning and exhausted gradually in the process for the other three disinfection methods. Similar plot trends had been reported previously [25].
At the optimal conditions selected, E. coli was completely inactivated in 40 min for the electrochemical disinfection. For ozonation, log inactivation reached 3.98 in 10 min. In order to facilitate comparison, a 4-log inactivation was selected as a standard for different disinfection methods. Corresponding CT (concentration x contact time) value was 33.5 mg min L⁻¹ for electrochemical process, and 1440 mg min L⁻¹ for ozonation. Log inactivation of E. coli got to 4 in 60 min for chlorine and it took 13 min for monochloramine process, and hence their CT values were expressed as 1575, 1674 mg min L⁻¹, respectively. Thus, E. coli was inactivated most effectively in electrochemical disinfection processes, and then ozone, chlorine and monochloramine in turn.

Electrochemical disinfection in Na₂SO₄ electrolyte is a green technology based on the ROS produced in electrolysis, including *OH, H₂O₂, O₃, *O₂, etc. Hydroxyl radical has the highest redox potential (Eₑ = 2.7 V) and thus is a main component in electrochemical disinfection, which had already been proved in many researches [13, 14]. Meanwhile, Li et al. [22] indicated that oxidants produced in the electrolysis of SO₄²⁻, such as S₂O₅²⁻, work in the disinfection.

Chlorine is a widely utilized and leading candidate disinfectant and the effective species is hypochlorite. It is electrically neutral, and then can easily approach and adhere on the bacteria cells. Meantime, molecular of hypochlorite is small, which is favorable for its diffusion into the cells. Although mechanism of microorganism inactivation by chlorine has not been fully elucidated, it can be speculated that microorganism cells would undergo changes in permeability in the chlorine disinfection, which had been proved by previous researches [26–28]. It is agreed that microorganisms inactivation by chlorination was due to the dysfunction in the internal enzyme group after the small molecule of chlorine diffusing through the cells [29]. Besides, chlorine may also react with the organic compounds within the cell wall, such as the N-terminal amino groups of proteins reported by Sharma et al. [30], to disrupt the cell original characters.

Inactivation ability of monochloramine is generally supposed to origin from hypochlorite released slowly. As a result, disinfection mechanism of monochloramine is same with chlorine, however, its disinfection ability is relatively poor.

Ozone used in water treatment can be considered as an oxidant and a germicide as well. White et al. [29] indicated that inactivation ability of ozone resulted from the bacteria cell wall disintegration and cell leakage. In the final analysis, the germicidal functions originate from its oxidizing ability.

Generally speaking, oxidation–reduction potentials of the four kinds of disinfectants are 2.70 V (hydroxyl radical) > 2.07 V (ozone) > 1.36 V (chlorine) > 1.13 V (monochloramine). In addition, hydroxyl radical is a strong oxidant without selectivity and existed as a free state in the BDD anode system [31, 32]. And hence electrochemical disinfection in Na₂SO₄ electrolyte proved to be superb to other disinfection methods due to the excellent character of *OH. As a result, E. coli inactivation availability could be ordered as electrochemical disinfection > ozonation > chlorine > monochloramine.

### 3.2. Inactivation tests for four different microorganisms

Efficacy of the four disinfection procedures was compared for four different bacteria. Fig. 2(a) presented the electrochemical inactivation of E. coli, S. aureus, BST and Bacillus at a current density of 20 mA cm⁻² in 0.2 M Na₂SO₄ electrolyte. It can be seen that all the four bacteria were inactivated very fast. Log inactivation achieved around 5 in 30 min for E. coli, S. aureus, and Bacillus at an initial bacterial concentration of 10⁵ CFU mL⁻¹, which means all the microorganisms were almost completely inactivated in 30 min in the electrochemical system.

Ozonation of E. coli, S. aureus, BST and Bacillus was given in Fig. 2(b) with an ozone concentration of 3 mg L⁻¹. E. coli was inactivated fastest compared to the other three bacteria, log inactivation reached 4 in 10 min. BST and Bacillus showed a slower disinfection efficacy and the two represented almost a consistent trend. The log inactivation in 10 min was less than 1.0 for BST and Bacillus.

Fig. 2(c) and (d) presented the chlorine and monochloramine disinfection of E. coli, S. aureus, BST and Bacillus with a concentration of 0.5 mg L⁻¹. It is referred that the optimal value of monochloramine disinfection was 2.5 mg L⁻¹ in the previous section. The purpose of the data selection here (at 0.5 mg L⁻¹) was mainly in the convenience to compare it with chlorine method, whose disinfection mechanisms were similar. It can be generally seen that both the inactivation processes in chlorine and monochloramine are quite similar with the trend shown in the ozone disinfection. As depicted in Fig. 2(c) and (d), E. coli was the most vulnerable bacteria with a log-inactivation of close to 4 in 60-min experiments. S. aureus was second to E. coli. Inactivation trend of the two bacillus bacteria proceeded rather slowly. In 60-min disinfection experiments, log inactivation of BST and Bacillus were less than 0.5 in both chlorine and monochloramine processes.

Disinfection availability of the four methods for each kind of bacterium followed the same order with E. coli as discussed in the previous section: electrochemical disinfection > ozonation > chlorine > monochloramine. Through comparison of the four disinfection methods, it can be known that the two bacillus were more recalcitrant to be inactivated than other bacteria in ozone, chlorine and monochloramine. However, the four kinds of bacteria presented almost the same trend in electrochemical disinfection. This can be attributed to characters of different bacteria and mechanisms of different disinfection processes.

Different bacteria have different peptidoglycan structures, i.e. mucoprotein in the bacterium cell wall. For example, E. coli (Gram-negative) forms the single layer scattered structure of plate mesh in a four-peptide side chain and is easily bonded to and invaded by the disinfectants to break the chemical bonds and to kill the bacteria. However, S. aureus and bacillus (Gram-positive) forms a cross-linked, three-dimensional spatial network structure of high mechanical strength in a four-peptide side chain that can only be bonded or invaded with difficulty by the disinfectants. Therefore, Gram-positive bacteria exhibit stronger drug–resistance than Gram-negative bacteria. Such as BST, Bacillus and S. aureus in this research [16]. Besides, compared with E. coli and S. aureus, the two bacillus are belong to a genus of Gram-positive rod-shaped bacterium, whose cells produce oval endospores that can stay dormant for extended periods under stressful environmental conditions. E. coli and S. aureus are the representative indicator microorganisms of vegetative bacteria, while BST and Bacillus represent the harsh microorganisms. As a result, in the disinfection of ozonation, chlorination and monochloraminization processes, BST and Bacillus presented the slowest inactivation, while E. coli was the most sensitive one to be inactivated.

It is known from the previous section that hydroxyl radical has the highest oxidation–reduction potentials in the four kinds of disinfectants. As a result, bacteria were inactivated fastest in electrochemical process. After electrolysis, complete inactivation of all the microorganisms was achieved in 30 min, which could be attributed to both the outstanding oxidation ability and the non-selectivity reaction of *OH [31–33]. At this point, the significant part of *OH in the electrochemical chloride-free disinfection was further confirmed based on comparison of different disinfection processes with four kinds of different bacteria. It is *OH existed in the free state with strong oxidizing ability in the BDD anode system that primarily controlled the non-selectivity of electrochemical
disinfection and thus could inactivate all the four bacteria in this study, even for the hash BST and bacillus.

3.3. SEM experiments

SEM was conducted to confirm the impact of different disinfection methods on these bacteria cells and to speculate the inner mechanism of these disinfection processes, shown as Figs. 3–6.

Fresh E. coli cells receiving no treatment were full and smooth on the surfaces (Fig. 3(a)). After electrochemical treatment, surface damage was observed. Fig. 3(b)–(d) showed the cell morphology of E. coli after electrolysis for 30, 60 and 150 min, respectively. It can be seen that some amount of intracellular materials was released from E. coli cells and then the cells were likely sticking to each other.
after 30 min electrochemical disinfection. These changes became more obvious after 60 min inactivation and cell lysis made the cell deform to a certain extent after 150 min electrolysis.

Liu et al. [34] attributed the mechanism of electrochemical disinfection to its disruption of bacterial membrane integrity and electrolysis of molecules on the cell surface. Diao et al. [14] suggested the high capacity of electrochemical disinfection may be provided by short-lived and energy-rich free radicals, which had a more powerful germicidal capability, such as •OH. These strong oxidants might kill microorganism cells by attacking the cell
wall and cell membrane, destroying the membrane integrity, or reacting with the organic molecules in the cell [35–37]. It is proved in this ESEM study that bacteria cells were gradually damaged and deformed along with the electrolysis process.

E. coli cells morphology after ozonation changed much less than that with electrochemical treatment, shown as Fig. 3(e). Cell leakage could be observed, though not obviously. Electron microscopic investigation of E. coli after direct chlorination and monochloramination in Fig. 3(f) and (g) showed no major change in their appearance, no surface destruction or cell lysis. The cell surface was as smooth as that of fresh cells. It is consistent with previous conclusions that chlorine disinfection does not affect the integrity of cells [14,15,29].

Changes of cell morphology after different disinfection methods for the other three bacteria of S. aureus, BST, Bacillus was the most obvious in electrochemical process, a little for ozonation and almost undiscovered in chlorine and monochloramine treatment, shown as Figs. 4–6. It should be made clear here that Bacillus isolated from Long River was extremely vulnerable in bombarding current field of ESEM, during which the cell surface quickly became black after even only one scan. As a result, SEM figures for Bacillus were all photoed in smaller magnification mode, in case of severe cell damage as possible. The black spots existed in Fig. 6(b) were indeed caused by current breakdown.

Above all, bacteria cells were inactivated through diffusion of these chemical disinficants into the cells and then reaction with the intracellular organics. For oxidants with high oxidation-reduction potential, such as •OH and O₃, cell surface damage is more significant due to the strong oxidation; For weak oxidants, such as chlorine and monochloramine, reactions with the cell wall are quite limited and then there is little cell surface deformation. Oxidation with the enzymes and other organics in the cell plasma might be the lethal reason.

4. Conclusions

Comparison of electrochemical method with ozonation, chlorination and monochloramination in drinking water disinfection was investigated in this paper, with four kinds of indicator microorganisms. The main conclusions can be summarized as follows:

1. Disinfection availability was ordered as electrochemical process > ozonation > chlorination > monochloramination when experiments were conducted at their respective optimal condition, in accordance with the oxidation–reduction potentials of the four kinds of disinfectants: hydroxyl radical (2.70 V) > ozone (2.07 V) > chlorine (1.36 V) > monochloramine (1.13 V). Then the special role of hydroxyl radical using BDD anode in electrolysis had been confirmed.

2. Disinfection efficacy was similar for the selected four bacteria in electrochemical process using BDD anode due to the non-selective and strong-oxidative hydroxyl radical in a free state as the disinfectant; while inactivation of BST and Bacillus was much slower than E. coli and S. aureus in the other three disinfection methods, which could be attributed to the harsh characters of BST and Bacillus as well as the weak oxidation ability of the other three disinfectants. The free hydroxyl radical primarily controlled the non-selectivity of electrochemical disinfection and its significant effect in the mechanism of BDD anode disinfection system was further explicitly concluded.

3. Attributing to the hydroxyl radical with non-selectivity and strong oxidizing ability involved in the mechanism of electrochemical disinfection with BDD anode, cell surface damage was
more obvious there into than that after ozone treatment, while the integrity of cells was not affected in weak oxidizing chlorine and monochloramine for E. coli, S. aureus, BST and Bacillus.

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