Influence of the Conductivity of the Discharge Liquid on the Microbicidal Effect of Transient Electric Arcs in Aqueous Systems

L. EDEBO, T. HOLME, AND I. SELIN

Institute of Medical Microbiology, University of Uppsala, Sweden, Department of Bacteriology, Karolinska Institutet, Stockholm, Sweden, and High Voltage Laboratory, Royal Institute of Technology, Stockholm, Sweden

Received for publication 1 November 1968

The microbicidal effect of electrical discharges on microorganisms suspended in the discharge liquid was reduced when the liquid contained high concentrations of inorganic salts (conductivity \( k \geq 5 \) mmho/cm). A higher discharge voltage and a smaller distance between the submerged electrodes counteracted this reduction. The decrease in the microbicidal effect was accompanied by a change in the electrical current and by a decreased yield of microbicidal photons from the electric discharge.

When high-voltage electricity was discharged through water, a multitude of physical effects and chemical compounds were generated, and microorganisms were killed (1). The microbicidal effect was mainly caused by ultraviolet (UV) light (2). Under certain conditions, chemical compounds also played an important role. The active compounds consisted of metallic material released from the electrodes and oxidants generated by the discharge (4, 6). The presence of inorganic salts in concentrations of 0.01 M (conductivity \( k \geq 1 \) mmho/cm) neutralized the chemical effects (4). In further experiments, it was found that at still higher concentrations of salts the microbicidal effect was completely extinguished.

MATERIALS AND METHODS

The electrical equipment, cultivation of bacteria, and viable counts were the same as described earlier (5). Escherichia coli B is more UV-resistant than E. coli B15. Unless otherwise stated, the capacitance (C) was 0.6 \( \mu f \), the inductance (L) was 46 \( \mu h \), and the volume of the discharge liquid was 1,200 ml. When suspensions of bacteria were discharge-treated, electrodes made from copper-tungsten alloy were used. The cells were suspended in solutions of different salt concentrations, and each suspension was subjected to one discharge. Other factors varied as described for the individual experiments. In some of the experiments for inactivating bacteria, the current through the liquid was measured.

The photon yield from the discharges was measured with a potassium ferrioxalate actinometer as described by Hatchard and Parker (7). The solution was kept in a quartz Erlenmeyer flask above a quartz window in the cover of the discharge vessel, and 100 discharges were released. These experiments were performed in the dark (for details see reference 3).

RESULTS

When E. coli B was suspended in KCl solutions and subjected to one discharge, the immediate microbicidal effect was generally little affected by a variation in the salt concentration from 0.001 to 0.01 M. At concentrations of 0.1 M and higher, the bactericidal effect was reduced. At 1 M KCl, no microbicidal effect was produced at a charging voltage (U) of 45 kv and an electrode separation (s) of 11 mm or at U = 32 kv and s = 8.3 mm. At U = 45 kv and s = 8.3 mm, there was a small microbicidal effect at 1 M KCl. In addition, at 0.1 M KCl, the microbicidal effect was greatest with this electrical adjustment (Fig. 1). A reduction in the microbicidal effect at high concentrations of salts was also observed with Saccharomyces cerevisiae in different concentrations of KCl and with E. coli B in different concentrations of sodium phosphate (Fig. 2). The microbicidal effect in 0.4 M sodium phosphate was greater with 57 kv than with 45 kv. At 57 kv, the medium was turbid immediately after the discharge but cleared up within 1 min. At 45 kv, the microbicidal effects in 0.4 and 0.04 M sodium phosphate were greater than in 1 and 0.1 M KCl, respectively. The conductivities of the phosphate solutions were lower than those of the respective KCl solutions. At low voltages (U = 32 kv), the microbicidal
effect was also reduced at very low concentrations of salt (Fig. 1). The sound of the bang accompanying the discharge varied greatly under these conditions. When a weak sound was heard or there was no sound, no killing effect could be measured. It is possible that the first discharge had the same effect as the one in 0.001 M KCl. On another occasion, six blind discharges were released until a real bang was heard. The value given in Fig. 1 for the suspension with no salt added is the mean of 16 discharges on different suspensions of which 5 were accompanied by the usual bang. Consequently, the estimation in Fig. 1 of the microbicidal effect at $U = 32$ kv with no salt added is a crude approximation.

In one series of experiments (Fig. 3), the peak current through the liquid and the time interval between the origin of the current and the instant when the current had decreased to half its peak value (time to the half value) were measured concomitantly with the instantaneous bactericidal effect on *E. coli* B15 (a UV-sensitive mutant) in different concentrations of KCl. As in Fig. 1, the microbicidal effect was reduced at 0.1 M KCl. At this concentration of KCl, the peak current was smaller and the time to the half value greater than at lower salt concentrations. At 1 M KCl, the bactericidal effect was extinguished and no discharge current was recorded; the current was probably too weak to trigger the current-measuring oscilloscope.

To get a rough estimation of the photon radiation from a single discharge in liquids of different salt concentrations, photographic films in transparent plastic envelopes were placed on the bottom of the discharge vessel and were subjected to one discharge at $U = 45$ kv and $s = 11$ mm (Fig. 4). Films immersed in tap water ($k = 0.4$ mmho/cm) became completely black (Fig. 4b), whereas films immersed in tap water containing 1

![Fig. 1. Effect of different concentrations of KCl on the bactericidal effect of one discharge on *E. coli* B. Symbols: □, $U = 45$ kv, $s = 8.3$ mm; △, $U = 32$ kv, $s = 8.3$ mm; ■, $U = 45$ kv, $s = 11$ mm.](fig1.png)

![Fig. 2. Effect of different concentrations of sodium phosphate on the bactericidal effect of one discharge on *E. coli* B. Symbols: □, $U = 45$ kv, $s = 8.3$ mm; ○, $U = 57$ kv, $s = 8.3$ mm.](fig2.png)

![Fig. 3. Effect of different concentrations of KCl on a discharge ($U = 45$ kv, $s = 11$ mm) with respect to peak current (▲), time to half value (▲), and viable count of *E. coli* B15 (■). Untreated suspension, 4 × 10^8 bacteria/ml.](fig3.png)
M KCl (k = 102 mmho/cm) did not become as dark (Fig. 4a). In the latter film, the shadows of the wires used for keeping the film from floating were seen clearly, whereas no such structures were observed when no salt had been added. Films immersed but not exposed to a discharge were clear (Fig. 4c).

The production of photons at different salt concentrations was measured with a K$_2$Fe(C$_2$O$_4$)$_3$ actinometer solution with a low sensitivity to radiation of wavelengths >500 nm. When a voltage (U) of 19 kv was released at an electrode separation of s = 4.5 mm in tap water (k = 0.4 mmho/cm), the yield of photons was calculated to be 1.9 × 10$^{18}$ photons per discharge (Table 1). When an equally large voltage was released through 1 m KCl (k = 102 mmho/cm), no photon activity could be measured. When the discharge voltage was increased with the other conditions unchanged, photon activity could be measured again. However, the yield of photons per joule was only 1:10 of that obtained from discharges in tap water.

**DISCUSSION**

The experiments have shown that when inorganic salts were present in the discharge liquid at concentrations giving a conductivity of about 5 mmho/cm or larger, the microbicidal effect on microorganisms suspended in the discharge medium was reduced. The degree of the reduction was shown to be dependent on the conductivity of the salt solution, the discharge voltage, and the electrode separation, such that the effect of a high salt concentration could be counteracted by increased capacitor voltage and decreased electrode gap (Fig. 1 and 2).

It has been demonstrated (2) that a large proportion of the immediate microbicidal effect of discharges is caused by UV radiation. The UV absorption of the discharge medium was little affected by the salts used. In contrast, the peak current of the discharge (Fig. 3) and the photon yield from the electric arc (Table 1) were markedly reduced. In some cases, the method used for measurement was not sensitive enough to recognize any current or photons. Therefore, it seems likely that the photon production was impaired at high conductivities. However, the transient turbidity observed after 57-kv discharges in 0.4 m sodium phosphate could have absorbed photons, and similar reactions might have occurred in other cases. To produce a measurable microbicidal effect from a submerged electric discharge, the formation of an electric arc is required (5). To bridge the electrodes with an arc, the electrode voltage must reach a minimal value, the breakdown voltage, which is dependent upon the salinity of the liquid between the electrodes, the electrode separation, and the capacitance. On account of the statistical nature of the breakdown process, which leads to the formation of high temperature plasma, the corresponding charging voltage has to be exceeded in order to get a high probability of breakdown in a series of discharges.

After the external air gap of the electric circuit has fired, the capacitor starts to push an ionic current through the liquid, and a voltage builds up across the submerged electrodes. The conductivity of the liquid, in combination with the values of C and L, determines which fraction of the initial charging voltage is applied to the submerged electrodes.

In the experiments with k < 5 mmho/cm (e.g., ≤0.01 m KCl), corresponding to a conductance of the test vessel of less than 14 mmho, the electrode voltage attained a value approximately equal to the charging voltage of the capacitor. When no salt was added to the liquid, k ≤ 0.01 mmho/cm, the breakdown of the liquid became erratic (Fig. 1; U = 32 kv). This might be ex-

![Fig. 4. Effect of the composition of the discharge liquid on the darkening of photographic films put on the bottom of the discharge vessel and subjected to one discharge; U = 45 kv, s = 11 mm, iron electrodes. Discharge liquid: (a) tap water with 1 m KCl; (b) tap water; (c) no discharge.](http://aem.asm.org/)

**Table 1. Effect of the composition of the discharge liquid on the production of photons by the discharge**

<table>
<thead>
<tr>
<th>Discharge liquid</th>
<th>Discharge voltage (kV)</th>
<th>Photons per discharge</th>
<th>Photons per joule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>19</td>
<td>1.9 × 10$^{18}$</td>
<td>1.7 × 10$^{16}$</td>
</tr>
<tr>
<td>1 m KCl</td>
<td>19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1 m KCl</td>
<td>29</td>
<td>4.4 × 10$^{17}$</td>
<td>1.7 × 10$^{16}$</td>
</tr>
</tbody>
</table>

* Iron electrodes were used; s = 4.5 mm.
plained by a rising dielectric strength of the liquid with decreasing salinity. In experiments with liquids of $k > 5$ mmho/cm (e.g. $\geq 0.1$ M KCl), the electrode peak voltage was less than the charging voltage because of considerable ionic current before the establishment of a plasma. When $k > 5$ mmho/cm, the voltage rise time approached $\pi/2$ times the square root of LC. In an experiment with 1 M KCl and $U = 45$ kv, the peak voltage was calculated to be 14 kv with a rise time of 7 $\mu$s. The heavy ionic current during such a relatively long rise time drained the capacitor of at least 90% of its initial energy, which may explain the low bactericidal effect at high salinity shown in Fig. 1 to 3, the less-pronounced darkening of the film in Fig. 4, and the low photon production in Table 1. In the experiments where no bactericidal and photochemical effect obtained and no photons were produced, the electrode voltage was probably too low to form an arc.

ACKNOWLEDGMENTS

The technical assistance of Lillemor Svensk is gratefully acknowledged.

This investigation was supported by grants from Gringesbergsbolaget and the Swedish Council for Applied Research.

LITERATURE CITED


