18aF-4

Chemical kinetics of plasma sterilization in liquid with the reduced pH method and the plasma treated water

低pH法ならびにプラズマ処理水による液中プラズマ殺菌の化学反応速度論

Katsuhisa Kitano [1], Satoshi Ikawa [2], Yoichi Nakashima [2], Atsushi Tani [3]

北野勝久 [1],井川聡 [2],中島陽一 [2],谷篤史 [3]

[1] Center for Atomic and Molecular Technologies, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan.

[2] Technology Research Institute of Osaka Prefecture 2-7-1 Ayumino, Izumi, Osaka 594-1157, Japan

[3] Department of Earth and Space Science, Graduate School of Science, Osaka University 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan

[1] 大阪大学工学研究科　アトミックデザイン研究センター　〒565-0871　大阪府吹田市山田丘2-1、

[2] 大阪府立産業技術総合研究所、[3] 大阪大学理学研究科

For the plasma disinfection of human body, we developed the reduced pH method, which brings strong bactericidal activity in the liquid with the lower pH conditions. Considering the applications of the plasma to human (body?), the plasma-induced chemical reactions in the liquid should be worthy of attention. The sterilization experiments in the liquid controlling pH and temperature have been conducted and these results have been discussed based on chemical kinetics. Bactericidal activities with direct plasma exposure were in proportional to the calculated HOO• concentrations at each pH. Plasma treated water (PTW) is also used for indirect plasma sterilization. Half-lives of PTW bactericidal activity depended on temperature and were in accordance with Arrhenius equation in the liquid PTW and the frozen PTW.

1. Plasma induced chemical reactions for plasma medicine

Based on unique characteristics of atmospheric pressure plasmas, novel plasma applications to human body 'Plasma Medicine' have attracted attention. Considering wet conditions of body systems, the concept of plasma process in liquid is essential. Various types of active species (ions, electrons, neutrals, radicals, UV, and so on) generated in plasma (gas phase) can be used for some desirable chemical reactions in liquid phase. For that purpose, atmospheric pressure plasmas with room temperature are suitable (Fig. 1), avoiding thermal damages to human body. Of course, not plasma itself but only some chemical species can penetrate into liquid to induce some chemical reaction. In other words, plasma is a sort of tool for producing reactive species. Although many applications in plasma medicine have been proposed, such a plasma-induced reactive species is known to be toxic to living organism. Our research target is the disinfection of human body, achieving beneficial use of these active species.

Fig. 1 Plasma jet exhausted to a finger without burning.

2. Effective sterilization by the reduced pH method

For disinfecting human bodies in dental [1] and surgical applications by low-temperature atmospheric-pressure plasmas, the important point to note is the inactivation of bacteria in body fluid. The reduced pH method was developed that strong bactericidal activity can be achieved if the solution is sufficiently acidic[2]. Drastic enhancement of bactericidal activity is obtained by controlling the pH of the solution under 4.7 and D value (1 log reduction time) became 1/100 when pH is changed from 6.5 to 3.8. D value at acidic condition can be controlled to quite small (< 2 sec) under some condition. We call this technique as the reduced pH method.

Because body fluid has neutral pH buffer capacity of pH ~7.4, this reduced pH method is essential technique for plasma disinfection. Just before plasma treatment of infected area, acidic fluid should be applied to its surface.

3. Physicochemical mechanism of the reduced pH method

Three kinds of bacteria were inactivated by direct plasma exposure under various pH conditions. Bacterial inactivation rates were proportional to concentrations of hydroperoxy radicals (HOO•) calculated by the theoretical model of chemical reactions (Fig. 2) [3]. Assuming the supply rate of superoxide anion radicals (O_2^-•) is constant, the concentration of HOO• is theoretically calculated to higher in lower pH (Fig. 3). To evaluate the penetration of radicals into the cell membrane, a bacterial model using dye-included micelles was used. Decoloration rates of the model were also in proportion with the calculated HOO• concentrations [3].

4. Physicochemical mechanism of temperature dependence of plasma treated water (PTW) activities based on chemical kinetics

In addition to direct and remote plasma exposures, plasma treated water (PTW) was confirmed to be effective with the reduced pH method. Half-lives of PTW bactericidal activity were in accordance with Arrhenius equation in the liquid and the solid state (Fig. 4). From the experimental results of ESR (electron spin resonance) measurement [4] of O_2^-• against PTW with spin trapping method, half-lives of PTW were also in accordance with Arrhenius equation (Fig. 4). Both activation energies are almost equal to ~110 kJ/mol. Half-lives at deep freezer temperature (-85 degree C) and body temperature (+37 degree C) are respectively estimated to 7 centuries and 3.9 seconds from Arrhenius equation, respectively. This indicates that PTW can be cryopreserved in freezer and toxicity to human body seems to be low due to fast disappearance of the bactericidal activity.

5. Summary

For further understanding of plasma medicine, experimental results must be discussed based on not the parameter of plasma generation but that of active species. In this paper, we discussed the effective plasma sterilization in liquid with the reduced pH method, based on the chemical kinetics concerning pH and temperature. These researches are fundamental and also will contribute to clinical application in the future.

Acknowledgments

This study was supported by Grant-in-Aid for Scientific Research B (23340176) and Innovative Areas "Plasma Medical Innovation" (25108505) from Ministry of Education, Culture, Sports,

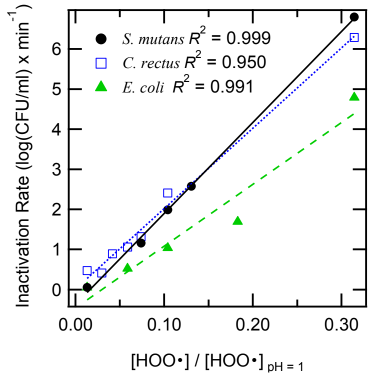

Fig. 2 Comparison between inactivation rates and concentrations of HOO•.

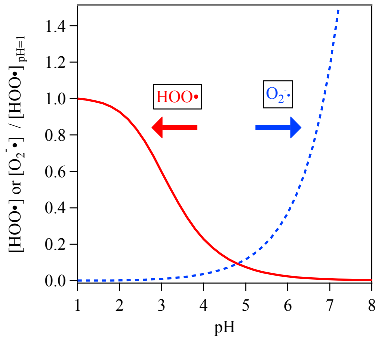

Fig. 3 pH dependency of concentrations of O_2^-• and HOO•.

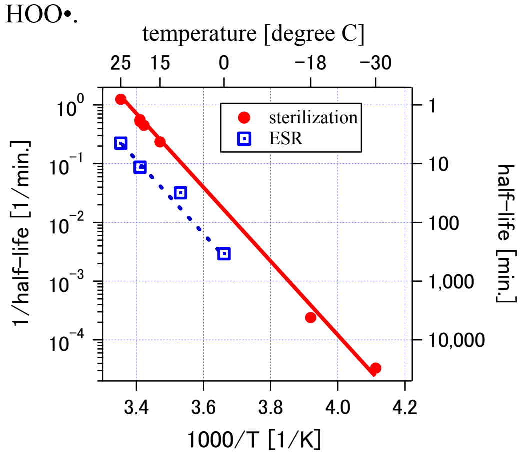

Fig. 4 Arrhenius plots for bactericidal activity and ESR measurement of PTW.

Science and Technology of Japan, A-STEP (AS2124901F) from JST, and the national cancer center research and development fund (23-A-15).

References

[1] H. Yamazaki et al., Dental Mat. Journal, 30, 384 (2011).

[2] S. Ikawa, K. Kitano, S. Hamaguchi, Plasma Process. Polym., 7, 33 (2010).

[3] E. Takai, S. Ikawa, K. Kitano, J. Kuwabara, K. Shiraki, J. Phys. D: Appl. Physics. 46, 295402 (2013).

[4] A. Tani, Y. Ono, S. Fukui, S. Ikawa, K. Kitano, Appl. Phys. Lett., 100, 254103 (2012).o, 1996, p. 93.