Vacuum 110 (2014) 217–220

Contents lists available at ScienceDirect

Vacuum

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

Sterilization of narrow tube inner surface using discharge plasma, ozone, and UV light irradiation

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ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form
3 June 2014
Accepted 13 June 2014
Available online 21 June 2014

Keywords:
Atmospheric pressure plasma
Dielectric barrier discharge
Plasma sterilization
Oxygen radical
Hydroxyl radical
UV

ABSTRACT

Sterilization of medical equipment is an important procedure in the field of medicine. However, methods for sterilizing medical equipment such as catheters or endoscopes have yet to be established. We developed novel sterilization methods to sterilize the inner surface of a tube using low-pressure discharge plasma, atmospheric pressure ozone, and ultraviolet (UV) light irradiation. Generation of active oxygen and hydroxyl (OH) radicals were measured by a chemical indicator and a spectrum analysis of light emission from the plasma. A biological indicator with *Geobacillus stearothermophilus* was used to evaluate the sterilizing ability. A tube 1000 mm long and 4 mm in diameter was successfully sterilized for 30 min using air and water vapor discharge. Furthermore, the atmospheric pressure method sterilized the tube in 1 min. Compared to conventional methods, sterilization using discharge plasma, ozone, and UV light irradiation is safe for the human body and harmless to the environment.

1. Introduction

In the field of medicine, sterilization of medical equipment is an important procedure for preventing infectious diseases. An autoclave is commonly used for sterilization of heatproof medical equipment. For sterilization of non-heatproof medical equipment, an ethylene oxide gas (EOG) method has been used. However, EOG is carcinogenic and the sterilization period is very long.

Recently, plasma sterilization methods have been developed as secure sterilization methods and have already been used for sterilizing medical equipment [1–6]. We have studied a low-temperature plasma sterilization method using oxygen [7–9]. In this method, we use only oxygen gas for the material gas and active oxygen species generated by the discharge function as the sterilization factor. After the treatment, active oxygen species instantaneously change to oxygen molecules. Therefore, this method is safe for the human body and harmless to the environment.

However, no method for sterilizing the inside of a tube such as a catheter or endoscope has been established. Recently, techniques for plasma generation inside a narrow tube using an atmospheric dielectric barrier discharge (DBD) or a microwave electron cyclotron resonance (ECR) plasma have been proposed [10,11]. In the DBD method, a wire-type electrode was inserted into a narrow tube and the tube was fixed to a ground plate to generate plasma uniformly. Controlling the sputtering from the electrode is very important to prevent contamination. The microwave ECR method enables the generation of plasma inside the tube without discharge from the electrode, but this method is costly and requires an enormous device.

In the present study, we developed novel sterilization methods to sterilize the inner surface of a tube using low-pressure discharge plasma, atmospheric pressure ozone, and ultraviolet (UV) light irradiation, and investigated the sterilization characteristics and changes in the surface structure of the tube.

2. Experimental procedure

2.1. Low-pressure discharge plasma method

Fig. 1 shows a schematic diagram of the low-pressure discharge device. The silicone rubber tube was placed in a stainless steel vacuum chamber 460 mm long and 210 mm in diameter and was evacuated to 10 Pa using a rotary pump. One end of the tube was connected directly to the rod-type discharge electrode. The material gases for plasma and radical production were air and water vapor, which were introduced to the electrode. The glowing discharge plasma, as shown in Fig. 2, was generated using an alternating current high-voltage (AC HV) power supply. The

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http://dx.doi.org/10.1016/j.vacuum.2014.06.014
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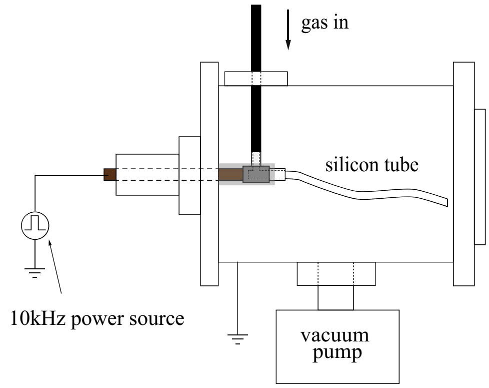

Fig. 1. Schematic diagram of low-pressure experimental apparatus.

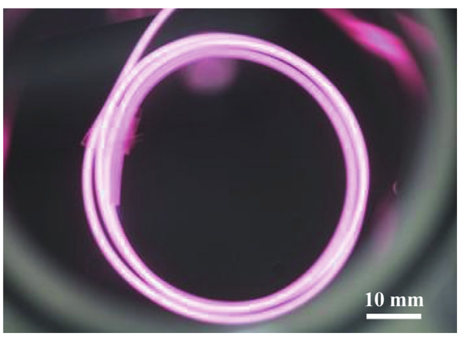

Fig. 2. Photographs of plasmas generated using air and water vapor. Chamber pressure and discharge voltage were 30 Pa and 5 kV_{p-p}, respectively.

discharge voltage and chamber pressure were 5 kV_{p-p} and 30 Pa, respectively. The generation of hydroxyl (OH) radicals was confirmed using a spectrometer (Soma Optics S-2630) and a chemical indicator. To investigate damage from discharge in the low-pressure method, the chemical bonds on the surface of the silicone tube after treatment were investigated using a Fourier-transform infrared (FTIR) spectrometer (JASCO FT/IR–4200) in attenuated total reflectance (ATR) mode.

2.2. Atmospheric pressure ozone and UV light irradiation method

Fig. 3 shows a schematic diagram of the experimental apparatus. The discharge device consisted of an inner rod powered electrode and a glass tube. The length and inner diameter of the glass tube were 130 mm and 4 mm, respectively. Using an AC HV power supply, dielectric barrier discharge plasma was generated in a space between the inner electrode and the glass tube. The discharge device was connected to the silicone tube to introduce ozone. The discharge voltage and flow rate from the air pump were 9.5 kV_{p-p} and 1.5 L/min, respectively. The ozone generated by discharge is dissociated to atomic oxygen and molecular oxygen by UV light irradiation according to the following reaction.

$$O_3 + h\nu(254\ \text{nm}) \rightarrow O_2(^1\Delta) + O(^1D) \quad (1)$$

The power consumption of the UV lamp was 10 W. The transmittance of the UV to the silicone tube was investigated using the spectrometer. The dissociation ratio of ozone in the silicone tube was investigated by measuring the absorbance of ozone with and without UV irradiation using FTIR.

2.3. Evaluation of sterilization of tube inner surface

To confirm the ability of each method to sterilize the inner surface of the tube, a strip-type biological indicator (BI) with a *Geobacillus stearothermophilus* population of 10^5 was inserted into the tube. The length and diameter of the tubes used in this experiment were 1000 mm and 4 mm, respectively. In the low-pressure method, BIs were placed 600 mm, 800 mm, and 1000 mm from the electrode. In the atmospheric pressure method, BIs were placed 250 mm and 600 mm from the electrode. We also attempted ozone or UV treatment individually to investigate the sterilization effects of the atmospheric pressure method. After the treatment, BIs were incubated for 24 h at a temperature of 58 °C.

3. Results and discussion

3.1. Low-pressure discharge plasma method

Fig. 4 shows typical light emission spectra from air and water vapor plasma inside the silicone tube at a discharge voltage of 5 kV_{p-p} and a pressure of 30 Pa. In the plasma, peaks for H_α, H_β, H_γ, OH, and OI were observed at wavelengths of 656, 486, 410, 306, and 777 nm, respectively. Moreover, the chemical indicator inserted into the tube turned a greenish color after treatment for 30 min, which indicates sufficient OH and oxygen radical.

Table 1 shows the sterilization results for the low-pressure discharge plasma method. Minus and plus signs indicate the success and failure of sterilization, respectively. After 30-min treatment, a tube 1000 mm long and 4 mm in diameter was sterilized. The bacillus utilized in this study was heat resistant and could not be inactivated even at 120 °C. The thermal label showed a maximum temperature of 80 °C inside the tube, meaning the bacillus was not inactivated by heat. The above results indicate that

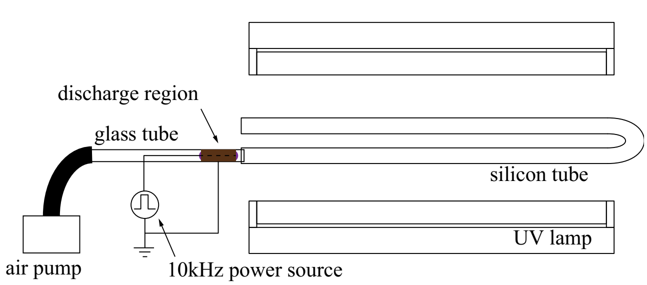

Fig. 3. Schematic diagram of atmospheric pressure dielectric barrier discharge torch device.

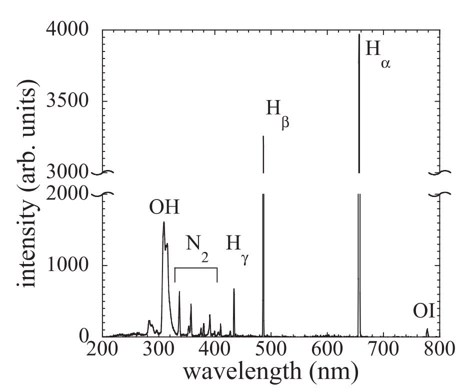

Fig. 4. Typical light emission spectra of air and water vapor discharge plasma inside the tube.