Study on Thermal Characteristics of Ionized Gas Coagulation Equipment

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ABSTRACT: Low energy ionized gas coagulation equipment (LE-IGCE) using low temperature nonthermal atmospheric pressure plasmas has been attracting special attention with the popularization of minimally invasive surgery. In this work, the thermal characteristics of a commercial high energy ionized gas coagulation equipment (HE-IGCE) and a specially designed LE-IGCE have been studied using an infrared camera and optical emission spectroscopy during their treatments. The four substrates used for the treatments were pork meats, copper (Cu) plates, wet tissues, and glass plates. In the HE-IGCE treatment, the surface temperature of the pork meat rose to 350°C, and the rotational temperatures of nitrogen molecules in plasmas were 450 to 1630 K, depending on which substrate was used during HE-IGCE treatments. In the LE-IGCE treatment, the surface temperature of pork meats was lower than 40°C, and the rotational temperatures of nitrogen molecules were lower than 350 K. The results show that the LE-IGCE can maintain the temperature of biological tissue below the threshold that would cause irreversible tissue damage.

KEY WORDS: plasma coagulation, low energy ionized gas coagulation equipment, high energy ionized gas coagulation equipment, minimally invasive surgery, thermal characteristics of plasmas

I. INTRODUCTION

Blood coagulation, which forms semisolid blood clots, is a protective process of the human body to heal damaged blood vessels and to stop the bleeding. Various medical electrical equipment has been widely used during surgery. High frequency electrical coagulator, ultrasonic wave equipment, and laser scalpel are typically used. Electrocoagulation equipment using atmospheric pressure plasmas has also been used in practical surgeries. Argon plasma coagulation (APC) is most commonly used to control bleeding during endoscopic surgery.[1] APC is a noncontact thermal method that uses high-frequency monopolar current conducted to target tissues through argon plasma. However, carbonization, vaporization, and deep tissue injury are induced with prolonged application.[2–4] Hereafter, the equipment is called high energy ionized gas coagulation equipment (HE-IGCE).

Minimally invasive surgery is becoming more common in hospitals. It has many advantages over conventional surgery, including faster recovery time, less scarring and pain, and a shorter hospital stay.[5] With the popularization of minimally invasive surgery, the development of new advanced medical technologies is a continuing requirement.

From these backgrounds, recently studies on the application of a nonthermal atmospheric pressure plasma to blood coagulation have been attracting special attentions as an alternative to thermal cauterization methods because it causes little damage to human tissue.[6–12] Hereafter, medical equipment using a low temperature nonthermal atmospheric pressure plasma is called a low energy ionized gas coagulation equipment (LE-IGCE). Fridmann et al.[9] observed blood clot formation using a floating electrode dielectric barrier discharge (DBD) plasma without visible or microscopic tissue damage. Kuo et al.[10,11] tested a nonthermal air plasma spray that produces plasma at relatively low temperatures below 55°C as an LE-IGCE for blood coagulation. Choi et al.[12] developed a 900 MHz atmospheric pressure argon plasma jet with low temperature below 47°C and studied the acceleration of blood coagulation. We also developed a specially designed nonthermal atmospheric pressure plasma flare based on DBD.[13–16] Here, plasma flare is defined as a visible light from the equipment to a target. The utility of the LE-IGCE as a minimally invasive plasma for blood coagulation was experimentally verified.[13,14] These works show that the LE-IGCE is a promising advanced electrocoagulation technology to control bleeding at low temperatures. The technology of the LE-IGCE is expected to reduce tissue damage without impairing the hemostatic effect and increasing the risk of postoperative disorders. For the practical application of the LE-IGCE for blood coagulation, more studies are needed to better understand how it differs from HE-IGCE, which is already in practical use.

In this work, we studied the thermal characteristics of plasmas in commercial APC equipment as an HE-IGCE and a specially designed nonthermal atmospheric pressure plasma flare as an LE-IGCE. In biomedical applications, the thermal characteristics of plasmas are very important factors, because the heating of biological tissues induces different effects that depend not only on the maximum temperature but also on the exposure time.[17] Over the past few years, many studies on the profiles of gas temperatures in nonthermal atmospheric pressure plasmas have been reported.[18–24] However, there are few studies on temperature profiles of plasmas produced by the HE-IGCE, so they are not yet fully understood. Here, we describe the thermal characteristics of plasmas produced by the HE-IGCE and LE-IGCE.

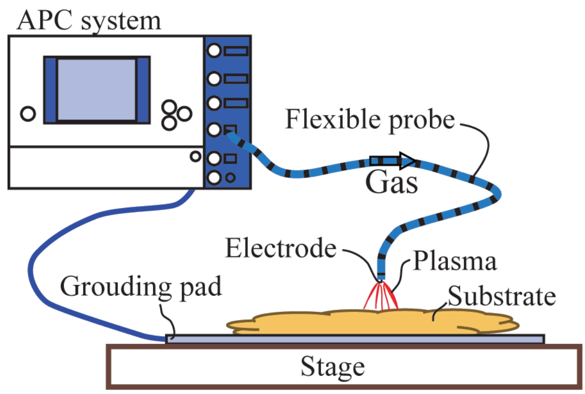

FIG. 1: A schematic illustration of a biomedical treatment using a commercial argon plasma coagulation (APC) equipment, which is the high energy ionized gas coagulation equipment (HE-IGCE).

II. EXPERIMENTAL DETAILS

The VIO APC 2 system of ERBE Elektromedizin GmbH and our nonthermal plasma flare were used for the HE-IGCE and LE-IGCE experiments, respectively. Surface temperatures in tissues and gas temperatures in plasmas were studied using an infrared camera and an optical emission spectrometry (OES), respectively. Fig. 1 shows a schematic illustration of a biomedical treatment using the HE-IGCE of commercial APC equipment. The APC is a monopolar electrosurgical technique that uses argon discharges at atmospheric pressure to ablate the tissue. The APC equipment consists of an APC 2 unit with a high frequency alternating current (AC) high voltage generator (typical frequency is 350 kHz and typical amplitude is 4 kV), an argon gas source, a flexible probe, and a grounded pad.[4] The flexible probe consists of a Teflon tube with a tungsten electrode. Argon gas, which is provided through the Teflon tube, surrounds the tungsten electrode. Plasmas are produced between the electrode tip and a substrate surface. The grounded pad is placed on the lateral substrate but is floated with respect to the earth.

Figure 2 shows a schematic illustration of a biomedical treatment using the LE-IGCE developed in this work. The LE-IGCE consists of a control box with a direct current (DC) power supply and a mass flow controller (MFC) and a plasma handpiece. DC power and gas are supplied to the plasma handpiece through a flexible cable and tube, respectively. A high frequency AC high voltage generator (typical frequency is 66 kHz and typical amplitude is 4 kV), which is operated by the DC power supply in the control box, is in the plasma handpiece. The LE-IGCE produces stable atmospheric pressure plasma flares based on DBD with helium gas. Plasmas are produced in a quartz tube. A high voltage electrode is equipped on the surface of the quartz tube. A trigger electrode is installed in the quartz tube. The high voltage electrode is completely covered by a dielectric layer to protect a human body.

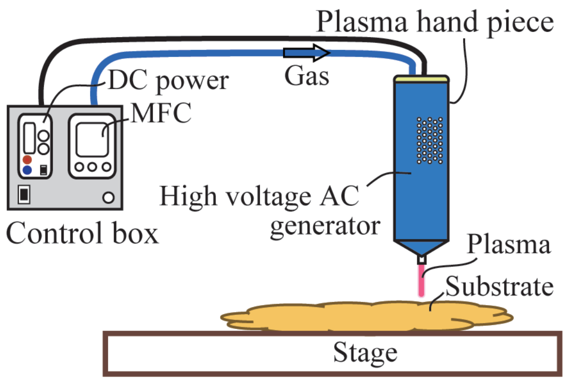

FIG. 2: A schematic illustration of a biomedical treatment using the low energy ionized gas coagulation equipment (LE-IGCE) developed in this work.

First, surface temperatures of pork meats were measured with an infrared camera (FLIR Systems, CPA-T640) during plasma treatments. The infrared camera provides a thermal image with an accuracy of ±2°C and a graph of the maximum temperature over time. Moreover, gas temperatures in plasmas were studied by measuring rotational temperatures of nitrogen molecules (N_2) using an OES (Ocean Photonics Inc., HR4000). Air components of plasmas produced by the HLE-IGCE and LE-IGCE are also excited and ionized, and optical emission spectra of nitrogen molecules are observed. Rotational temperatures are obtained by fitting the experimentally observed spectrum of the second positive band of N_2 with the numerically calculated one.[25–27] However, it was difficult for us to identify the spectrum lines of the second positive band during HE-IGCE treatments of pork meat, because the spectrum lines of impurities from the pork masked the spectrum lines of the second positive band of N_2. For this reason, three substrates—copper (Cu) plates, wet tissues, and glass plates—were used instead of pork for the rotational temperature measurements in this work.

III. RESULTS AND DISCUSSION

For tests conducted with the HE-IGCE and LE-IGCE, surface temperatures of the pork meat were detected using the infrared camera during plasma treatments. Figure 3(a) shows a picture and a thermal image of the HE-IGCE treatment. Figure 3(b) shows the variation of the maximum temperature on the pork at the contact point with the plasma. The HE-IGCE was operated with an electrical power of 25 W and an argon gas flow rate of 2.0 L/min. The thermal images show that the contact points with the plasma are strongly heated. The maximum temperature of the pork at the contact point ranged from 100°C to 350°C. The desiccation, evaporation, and carbonization of pork tissues were visible without magnification. It is known that, in practical HE-IGCE applications, high frequency currents introduced at the electrode tip are transmitted to tissues and a grounded pad through ionized argon gas. The currents cause ohmic heating in the tis-

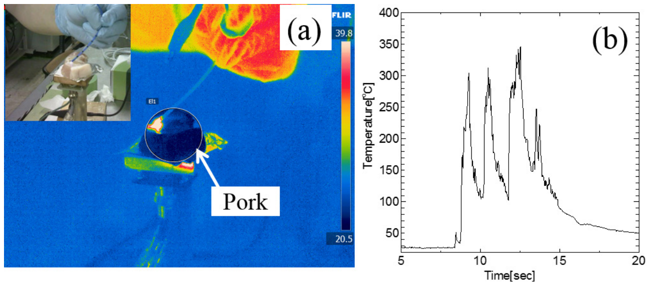

FIG. 3: (a) A picture of the HE-IGCE treatment for of pork meat and its thermal image detected using an infrared camera. (b) The variation of the maximum temperature on the pork of the contact point with plasmas (operating conditions: electrical power, 25 W; argon gas flow rate, 2.0 L/min).

sues, which is described in detail by Sakakita et al.[28] The desiccation, evaporation, and carbonization of pork tissues increases electrical resistance in the treated area, resulting in the variations of currents and temperatures. Also, this causes the current to move to another point on the tissue surface where resistance is lower.[3]

Figure 4 shows a picture and a thermal image of the LE-IGCE treatment of a pork sample. The maximum temperature on the pork meat of the contact point is below 40°C. The plasma flare produced by the LE-IGCE blows from the quartz tube to the pork meat with a gas flow. Optical emissions of the plasma flare and temperatures on the pork meat at the contact point are almost constant during the LE-IGCE treatment. It has been reported that the plasma flare shows a stationary plasma striation between the quartz tube and a substrate.[16] These results indicate that the variation of the operating characteristics of the plasma flare is relatively small during the LE-IGCE treatment.

Optical emission spectra from plasmas produced by the HE-IGCE were measured using an OES to study rotational temperatures of N_2 in the plasma. The measurements were carried out using Cu plates, wet tissues, and glass plates as substrates. Figures 5 and 6 show a typical picture of optical emissions and optical emission spectra of the N_2

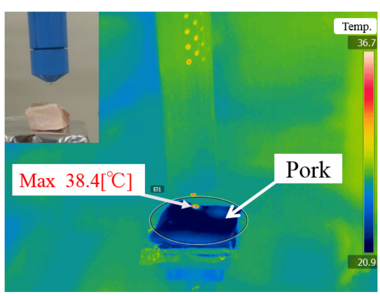

FIG. 4: A picture and thermal image of the LE-IGCE treatment of pork and its thermal image detected using an infrared camera (operation conditions: helium gas flow rate, 2.0 L/min).

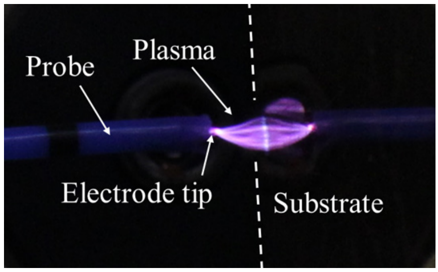

FIG. 5: A picture of the plasma produced by the HE-IGCE. Filament-like discharges are produced in the plasma between an electrode tip and a substrate surface of copper. There is a duplicate image of the plasma reflected by the substrate surface on the right side of the picture.

second positive band in the plasmas produced by the HE-IGCE. The plasma is produced between the electrode tip of the flexible probe and a substrate surface. A number of filament-like discharges randomly occur between the electrode tip and the substrate surface in the plasma. The observed optical emission spectra are vary over time as shown in Figure 6, which shows 10 spectra with a time step of 0.5 sec when wet paper was used as a substrate. Each spectrum was averaged with an exposure time of 0.08 sec. The variation of optical emission spectra over time is related to the known discharge phenomenon of a conventional HE-IGCE. As previously mentioned, in the HE-IGCE, the flow of alternating currents is induced from the electrode tip and the grounded pad through ionized argon gas and tissue. The filament-like discharge directs itself to the substrate with the lowest resistance.[2–4] This causes the random occurrence of filament-like discharges and the variation of the optical emission spectra over time.

An optical emission spectrum with the strongest line emission intensity in the spectra was used to obtain a rotational temperature, which were derived by fitting the experimentally observed spectrum with the numerically calculated one. Figure 7 shows

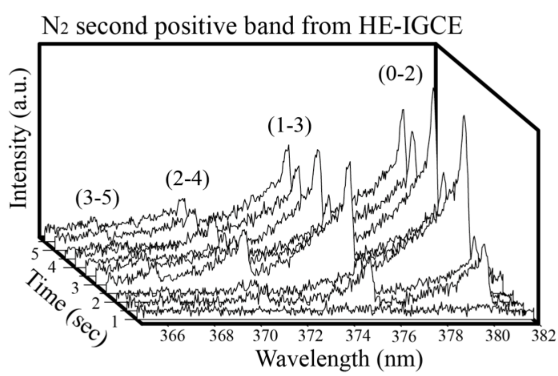

FIG. 6: Typical optical emission spectra of the second positive band of N_2 from plasma produced by the HE-IGCE. A wet tissue was used as the substrate. The observed optical emission spectra randomly vary with time. The time step of the observation is 0.5 sec.

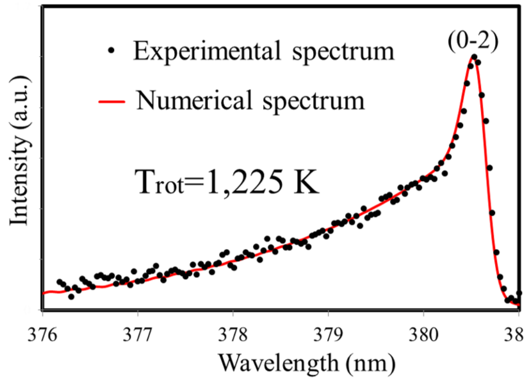

FIG. 7: An example of fitting an experimental spectrum with a numerical spectrum of the second positive band (0-2) of N_2. The fitting shows that the rotational temperature of N_2 in plasmas produced by the HE-IGCE is around 1,225 K when wet paper is used as a substrate.

an example of the spectrum fitting. The experimental spectrum, which was obtained from plasmas with an argon gas flow rate of 2.0 L/min, an electrical power of 20 W, and a substrate of a wet tissue, is fitted well by a numerical spectrum calculated with a rotational temperature of 1,225 K. From this fitting, we can determine that the rotational temperature of N_2 in the plasma is around 1,225 K.

Rotational temperatures of N_2 in plasmas were studied with three substrates, a Cu plate, a wet tissue paper, and a glass plate (thickness approximately 0.15 mm). The experiments were performed with three operation conditions of the APC equipment: (1) 30 W and 2.0 L/min, (2) 30 W and 2.4 L/min, and (3) 20 W and 2.4 L/min. The results are plotted in Figure 8. The rotational temperatures were 1,300 to 1,630 K on the Cu plate, 1,150 to 1,400 K on the wet tissue paper, and 450 to 650 K on the glass plate. The results

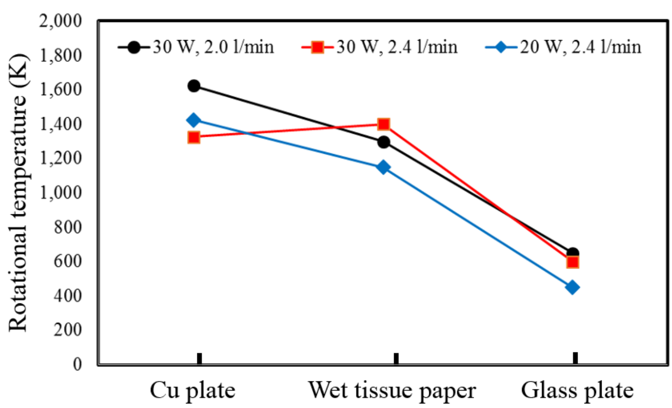

FIG. 8: Rotational temperatures of N_2 in plasmas produced by the HE-IGCE with three substrates: a Cu plate, wet tissue paper, and a glass plate.

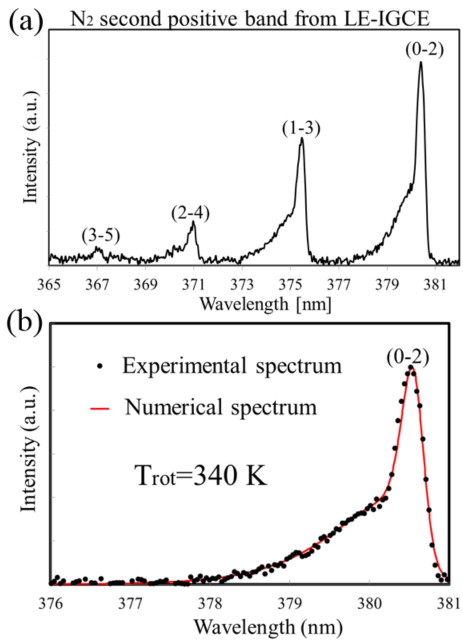

FIG. 9: (a) A typical spectrum of the second positive band of N_2 sec from plasmas produced by the LE-IGCE with a helium gas flow rate of 2.0 L/min, and (b) a fitting of an experimental spectrum and a numerical spectrum of the second positive band (0-2) of N_2. The fitting shows that the rotational temperature of N_2 is approximately 340 K.

show that the change of substrate causes relatively large changes in rotational temperatures. Electrical resistance increases in the order of the Cu plate, wet tissue paper, and glass plate, which indicates that the increased current flow between the electrode tip and substrates raises the gas temperature in plasmas.

Figure 9(a) and (b) show a typical spectrum of the second positive band of N_2 from plasmas produced by the LE-IGCE with a helium gas rate of 2.0 L/min and the fitting of the spectrum with a numerical spectrum to obtain the rotational temperature with respect to a Cu plate, respectively. The spectrum shown in Figure 9(a) was averaged with an exposure time of 0.5 sec. The optical emission spectra in the LE-IGCE are continuously observed. The fitting shown in Figure 9(b) indicates that the rotational temperature is approximately 340 K. This means that gas temperatures produced by the LE-IGCE are much lower than those produced by the HE-IGCE. In the LE-IGCE, AC currents can flow as pulsed currents from a high voltage electrode to a substrate through the dielectric, the gas space, and the plasma flare. The average current density in the gas space and plasma flare are limited by the dielectric layer covering the high voltage electrode,[29] resulting in limited ohmic heating of the substrates.[28]

IV. CONCLUSIONS

We described the thermal characteristic of plasmas produced by a commercial HE-IGCE and compared them with the properties of plasmas produced with the LE-IGCE. Surface temperatures on tissues and rotational temperatures of N_2 in plasmas were studied using an infrared camera and optical emission spectrometry, respectively. The surface temperature on pork meat is raised to 350°C during the HE-IGCE treatment. Rotational temperatures in plasmas produced by the HE-IGCE ranged from 450 to 1630 K, depending on the substrate. During the LE-IGCE treatment, the surface temperature and the rotational temperature are lower than 40°C and 340 K, respectively. These results indicate that the LE-IGCE can limit the heating of biological tissue, preventing irreversible tissue damage. Therefore, it should prove useful as an electrocoagulation device during minimally invasive surgery.

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