Novel DLC Coating Technique on an Inner-wall of Extended Polytetrafluoroethylene Vascular Grafts Using Methane Plasma Produced by AC HV Discharge

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1. Introduction

A Diamond-Like Carbon (DLC) film that was deposited by a plasma process using an electric discharge corresponds to an amorphous carbon-based film with an irregular boundary structure that contains intermingled sp3 bonds of diamond and sp2 bonds of graphite [1] and various other types of DLC films have been reported [2]. Generally, DLC films have been attracting increasing attention to be used in industrial applications as protective films for car components and machine parts as well as in bio-compatibilized films that can be used in case of medical equipment because of their high degree of hardness, low friction coefficient, abrasion and corrosion resistance, chemical stability, biocompatibility, and gas barrier property [3-5]. Recently, following the production of coronary artery stents [6,7], highly biocompatible DLC films are considered for usage in medical implants such as dental implants [8,9]. Additionally, hydrophilicity and hydrophobicity can be easily imparted to a DLC film surface by plasma surface treatment [10], and the surface zeta potential can be controlled [11]. By exploiting this property and by modifying the surface property of the DLC film, it can possibly exhibit ideal biocompatibility and efficiency for each organ. Thus, the DLC film can become valuable as a next-generation coating.
material for medical equipment.

The population of most of the developed countries is currently increasing, and there is an increase in the requirement of various kinds of artificial vascular grafts because of the increasing number of patients with arterial vascular diseases. However, the patency rate of a vascular graft with a small diameter is not sufficient. Extended-polytetrafluoroethylene (ePTFE), the most popular material for small-diameter artificial vascular graft, exhibits a hydrophilic surface and excellent biocompatibility [12]. However, the patency rate is quite low when the ePTFE vascular graft is used to perform a below-knee arterial bypass or hemodialysis shunt because of the stenosis that is caused due to neointima formation or thrombosis in the vascular graft [13,14]. Development of a new artificial vascular graft is necessary for achieving a higher patency rate in vascular surgery with small vessels.

Previously, cell adhesion using a DLC-coated PTFE film has been reported [15,16]. An improved patency rate is expected by coating a DLC film onto the inner wall of the ePTFE vascular grafts. Furthermore, for coating DLC onto the inner capillary surface, the Plasma Based Ion Implantation (PBII) [17,18] and Microwave sheath-Voltage combination Plasma (MVP) [19,20] methods have been recently proposed; however, these methods are only suitable for the deposition of DLC onto the inner wall of a short metal capillary, and there are very few studies that have investigated the deposition of DLC onto the inner wall of a small-diameter long-sized resin tube.

Hence, in this study, a novel AC high-voltage methane plasma Chemical Vapor Deposition (CVD) method is proposed, which intends to develop a technique for depositing a Hydrogenated Amorphous Carbon (a-C:H) film on the inner wall of the small-diameter long-sized resin tubes. This deposition method will impart 1) malleability to the DLC film and permit 2) low-temperature coating and 3) coating of the inner surface of a tube, all of which are different from that observed in conventional deposition methods. The aforementioned characteristics will realize applications, such as vascular grafts, catheters, artificial cardiopulmonary circuits, and dialysis circuits, with an expected reinforcement in medical applications.

2. Experimental

Figure 1 shows the schematic of the system configuration of the DLC deposition equipment by utilizing the developed AC high-voltage methane plasma CVD method. A chamber size with an inner diameter and length of 200 and 500 mm, respectively, was designed by considering the application of coating the inner surface of long-sized catheters. The plasma power supply comprised a function generator (SG-4104, Iwatsu Electric Co., Ltd.) as a voltage generator and an amplifier (HVA4321, NF Corporation), and the measurements were conducted using a voltage of ±10 kV pk, a peak current of ±60 mA, and a frequency of 45 kHz. The current–voltage characteristics were measured using a digital oscilloscope (2000 X-Series, Agilent InfiniiVision). Table 1 summarizes the deposition conditions. Prior DLC film deposition, the interior of the chamber was evacuated to less than $9 \times 10^{-3}$ Pa. Methane gas was used as the source gas, which depicted a flow rate of 96 sccm by a mass flow controller. At an operational pressure 39 Pa along with a constant AC voltage of 5 kV and a frequency of 10 kHz as the deposition conditions, the electrode was placed on only one side of a small-diameter long tube, and voltage was applied with the chamber serving as the earth.

Table 1. Operating conditions of the AC HV discharge.

| Parameter             | Value          |
|-----------------------|----------------|
| AC voltage            | 5 kV           |
| Frequency             | 10 kHz         |
| Offset voltage        | 2 kV           |
| Pulse per second      | 10 pps         |
| Source gas            | Methane        |
| CH$_4$ flow rate      | 96 sccm        |
| Deposition time        | 5 min          |
| Base pressure         | $9 \times 10^{-3}$ Pa |
| Operational pressure  | 39 Pa          |
electrode. Additionally, with an increasing input voltage, the sample temperature was observed to increase at the time of deposition; therefore, a pulse repetition of 10 pulse-per-second (pps) on frequency (burst waveform) is set on the function generator to control the increase in temperature. Further, for improving the adhesive ability of the film, the function generator was set to an offset negative voltage of 2 kV. The ePTFE vascular graft (ePTFE graft II, Japan Gore Ltd.) was used as the sample. The inner diameter and length of the sample were 4 and 150 mm, respectively. However, the ePTFE vascular graft with a porous structure cannot confine the methane plasma within the tube; hence, plasma confinement is attempted by loading the vascular graft inside a silicon tube with inner and outer diameters of 5 and 7 mm, respectively. Further, it is difficult to analyze the structure of the deposited a-C:H film using a Raman spectroscopic analyzer (RAMAN11, Nanophoton Corporation) because of the porous structure of the vascular graft. Hence, the surface structure of the deposited a-C:H film is analyzed using a tube that comprised the same PTFE as a substitute. Measurement conditions included a laser light-source wavelength of 532 nm, an objective-lens magnification of 50X with a numerical aperture (NA) of 0.8, a diffraction grating of 600 gr/mm², and a laser intensity of ~0.5 mW.

A preliminary animal study was performed on beagles to evaluate the effects of the newly developed DLC-coated ePTFE vascular graft. The animal was anesthetized using an intramuscular injection of ketamine and by making the animal to inhale isoflurane. The carotid artery of the animal was replaced with a DLC-coated or non-coated ePTFE vascular graft. The animal survived for 8 weeks after the operation and was then euthanized. The histological patency of the ePTFE vascular graft and bioactivities against vascular grafts were evaluated and compared between that of the DLC-coated ePTFE vascular graft and non-coated ones using a Hematoxylin-Eosin stain. All the beagles were housed in a barrier facility, with ambient temperatures ranging between 20 °C and 24 °C. The beagles were fed diet and water ad libitum. The experimental protocol was approved by the Ethics Review Committees for Animal Experimentation of Okayama University Graduate School of Medicine, Dentistry, and Pharmaceutical sciences.

3. Results and discussion

3.1. Development of the AC high-voltage methane plasma CVD method

Figure 2 shows a photograph that is related to the formation of methane plasma on the inner surface of the ePTFE vascular grafts. Methane plasma was uniformly formed inside the small-diameter long tube from the side of the electrode toward the end of the tube. Its discharge principle is simple. Methane plasma was produced by applying an AC high-voltage power supply to the electrode in a similar manner to that of the glow discharge within a Geissler tube, from the side of the electrode toward the end of the tube, and by exploiting the pressure difference between the inside and outside of the tube. Additionally, the glow discharge inside the silicon tube with an aspect ratio of 750 (inner diameter of 2 mm and an overall length of 1,500 mm) and the PTFE tube was verified; hence, the formation of methane plasma inside a small-diameter long resin tube was observed to be possible. Figure 3 shows the voltage–current waveforms at the time of discharge. A pulse-like discharge current was repeatedly observed because of the increase and decrease in voltage. Because of the periodical increase and decrease in the discharge current, a stable discharge was maintained. Further, using a thermolabel (WAHL) during deposition, the internal tube temperature
was observed to range from 132 °C to 154 °C, and low-temperature deposition was observed. Although PTFE melts at 327 °C, deterioration is observed to begin from 260 °C. Hence, the developed low-temperature plasma CVD method permits deposition without causing any material deterioration.

3.2. Valuation of the DLC coating

Figure 4 shows the Raman spectra of the DLC film that was formed on the inner wall of the PTFE tube (4 mm inner diameter) at different deposition times. Figure 4 (a) depicts the Raman spectrum of the inner wall of the untreated PTFE tube; (b), (c), and (d) depict the same at a deposition time of 5 min, 20 min, and 40 min, respectively. The deposition conditions of (b), (c), and (d) were maintained to be constant at an AC voltage of 5 kV and a frequency of 10 kHz, and only the deposition time was modified. For a short deposition time, it was difficult to detect the Raman peak because of a thin DLC film; therefore, the characteristic peak of PTFE is observed using the Raman spectrum of (b). Additionally, the intensity of the characteristic peak for PTFE in the Raman spectra gradually decreased with increasing film thickness. At a deposition time of 40 min, a sharp peak was not observed. The vicinity of the G peak (Graphitic), which was observed at 1590 cm\(^{-1}\), that corresponds to the bond stretching vibration of a pair of sp\(^2\) sites and the D peak (Disordered), which was observed at 1350 cm\(^{-1}\), that corresponds to the disorder in sp\(^2\) bonds were observed to be broad [1,2]; therefore, a typical DLC structure was suggested. Figure 5 shows the Field-emission Scanning Electron Microscope image (FE-SEM; SU8010, Hitachi Ltd.) of the inner wall of an ePTFE-deposited vascular graft. Although the material exhibited a porous structure, uniform deposition was observed without any material deterioration; this was related to the low-temperature deposition that was made possible by setting the pulse repetition on frequency at 10 pps (burst waveform) on the applied AC voltage.

3.3. Animal experiments using DLC vascular grafts

The biocompatibility of the ePTFE vascular grafts using the DLC (a-C:H) film, which was coated by AC high-voltage methane plasma CVD, was assessed by animal experiments described above. The carotid arteries of the beagles were replaced with grafts, and the differences in histological bioactivities between the DLC-coated ePTFE vascular grafts and the typical ePTFE vascular grafts were compared. Figure 6 presents

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**Fig. 4.** Raman spectra of the a-C:H films on the inner wall of a PTFE-based tube.

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**Fig. 5.** SEM image of the inner wall of the ePTFE vascular grafts after deposition.

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**Fig. 6.** Histologic sections that were obtained from the carotid artery. Beagles survived for 8 weeks. The neointima was thinner and more uniform on the DLC-(a-C:H) coated ePTFE as compared to that on the normal ePTFE vascular grafts.
the results of the pathological evaluation. A considerably thinner and more uniform vascular intima was spread out on the DLC-coated inner ePTFE surface. However, untreated ePTFE exhibited inconsistent intimal thickening. Additionally, there was a dissection of the neo-intima (divided into two parts). The growth of uniformly thin neo-intima is very important for the long-term patency of the vascular graft. Therefore, if different observations were caused due to the a-C:H film inside the vascular graft, it indicates that the DLC coating is a very promising coating material that can be used for vascular grafts.

4. Conclusion

In this study, an AC high-voltage methane plasma CVD method was proposed, and a technique to coat a-C:H on the inner wall of a small-diameter long resin tube was attempted. Results confirmed the confinement of methane plasma in the small-diameter long tube of the ePTFE vascular grafts (diameter of 4 mm and overall length of 150 mm) and the formation of a thin a-C:H film on the inner wall by Raman analysis. Additionally, according to the results of the animal-based study, it can be inferred that the a-C:H film may contribute to the formation of uniform and thin neo-intima in the ePTFE vascular grafts.

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