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ORIGINAL ARTICLE

Biomaterials

Triboelectric charging of polytetrafluoroethylene antithrombotic catheters

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Abstract

This study proposes that a polytetrafluoroethylene (PTFE) electret tube charged by frictional electricity can prevent the solidification of the indwelling catheter in blood vessels. Coagulation in intravascular indwelling catheters may discontinue the treatment because of thrombus-derived bacteria–adhesion infections or poor blood removal. Current commercially available intravascular catheters lack complete antithrombotic measures, even with heparin or urokinase antithrombotic coatings. Herein, we tested the effectiveness of an antithrombotic treatment that prevents coagulation using a static electric charge on the interior of the PTFE tube via the triboelectric effect by rubbing the tube's inner wall with a round glass rod. The anticoagulation properties were evaluated by enclosing a sample of blood in an electret tube and observing the coagulase adhering to the inner wall using a microscope. To confirm the effectiveness of this treatment, the charge–distribution on the inner surface of the electret tube was measured, surface irregularities were observed, and the elements on the surface were analyzed. The surface potential inside the electret tube was − 366.4 V, which proved effective for an antithrombotic treatment, as it discouraged coagulation, and the triboelectric charging process caused neither surface element denaturation nor significant surface irregularities. The nearly uniform negative surface charge on the inside of the tube was responsible for the antithrombotic effect because no surface irregularities or change in the surface element denaturation was observed. Triboelectrically charged PTFE electret tubes are highly useful for intravascular indwelling catheters.

Keywords Electret · Intravascular indwelling catheter · Triboelectric charging · Anticoagulant

Introduction

Catheterization is an option for vascular access (VA) when a patient requires emergency blood purification or dialysis. According to a survey of patients undergoing chronic dialysis conducted by the Japanese Society for Dialysis Therapy in 2016, infectious diseases are the leading cause of death in patients undergoing dialysis, accounting for 26.4% of deaths in that year [1]. Among the deaths caused by infectious diseases, catheter-related bloodstream infections (CRBSIs) account for a large proportion [2]. The main etiological factor for CRBSIs is the instrument material, the host factor is protein attachment, and the pathogenic factor is unique to the infecting microorganism [3]. *Staphylococcus aureus* is the most common organism that causes CRBSI [4] and is normally present in the flora of the human body. Generally, it is found in the nose, respiratory tract, and skin. *Staphylococcus aureus* can also be highly pathogenic and cause various diseases ranging from suppurative inflammation to sepsis [5]. The infection risk from a non-cuffed catheter is 25.5 times higher than that caused from an inner-shunt arteriovenous fistula; furthermore, the infection rates in terms of non-cuffed catheters are much higher than any other form of VA [6]. Fevers and infections associated with catheter placement often progress to sepsis or septic shock, especially, in patients with renal failure or elderly patients with impaired immune functions. Sepsis affects the patient's prognosis

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significantly. One of its most common causes is the thrombus that forms on the outer surface of a catheter, acting as a hotbed for bacteria [7]. In addition, the thrombi caused by coagulation inside the catheter can impede blood removal, leading to the interruption of the treatment, and removal of the catheter [8, 9]. Against this background, there is a need to develop an additional antithrombotic catheter [10].

To counteract the formation of thrombi in intravascular indwelling catheters, we studied negatively charged hydrophobic materials. Ogino et al. [11] investigated the use of an electret film made by corona discharge and confirmed its antithrombotic properties. However, corona discharge is a difficult way to generate a constant surface potential on the interior of a long piece of material like that used in an indwelling catheter. Triboelectric charging, the transfer of electric charges between different materials through friction, should be easier to apply to a long piece of material. However, temperature and humidity affect the triboelectric effect, so we investigated the relation between temperature, humidity, and the surface potential when manufacturing an electret tube. In addition, to confirm the uniform charging of the triboelectrically charged electret surface, the charge–distribution was measured. Since polytetrafluoroethylene (PTFE) is a polymer material [12] with low thermal conductivity and the inner surface of the tube was observed to reveal the effects of the heat generated by friction. Furthermore, scratches on the surface due to triboelectric charging were observed with an electron microscope and it was confirmed that there was no relation with blood coagulation [13].

Materials

The materials and equipments used are given below.

A 10 mm long PTFE tube (inner diameter 6 mm, outer diameter 7 mm), a glass rod of 20 cm in length (6 mm in diameter), surface potentiometer (model 520; TREK Inc, USA), a charge-distribution toner (AK30-C; Kasuga Electric Co., Ltd, Japan), a photoelectron spectrometer (JPS-9200; Japan Electron, Japan), an electrolyte emission electron microscope (JSM-6060 LV; JEOL Ltd, Japan), upright microscope with 10× magnification (DMLB; Leica, Germany), and a single-lens digital camera (α7S, Sony, Japan).

Methods

Triboelectric charging of PTFE tubes and surface potential measurements

Triboelectric charging was used to manufacture an electret surface on the insides of the basic PTFE tubes. PTFE tends to take a negative charge according to the triboelectric series, whereas glass tends to take a positive charge [14]. A glass rod (6 mm in diameter) was inserted into a 10 mm long PTFE tube (inner diameter: 6 mm, outer diameter: 7 mm). To negatively charge the inside of the tube, a glass rod of length 20 cm was manually passed through PTFE five times in 5 s. In preliminary tests, this preparation method yielded a constant surface charge. The surface potential was measured by cutting open a treated PTFE tube longitudinally and cutting the 10 mm strip of the material into a film shape. Then, a surface potentiometer (model 520; TREK Inc, USA.) was used to take measurements, with 5 mm gap between the sample and the potentiometer. The surface potential was measured at the central part of the sample and at a total of five points around the inner circumference of the tube. The average and standard deviation of the surface potential were calculated.

Furthermore, the charge distribution was observed using a charge-distribution toner (AK30-C; Kasuga Electric Co., Ltd, Japan). This fine-charged power allowed us to quickly visualize a charge pattern by applying the powder directly on the sample. When the powder adheres, the toner turns red when it is negatively charged and blue when it is positively charged [15].

Next, the surface potential of the triboelectrically charged surface was influenced by temperature and humidity assuming the production of an electret in the clinical setting environment. Therefore, the relation between temperature/humidity and surface potential during electret manufacturing was investigated [16].

Verification of surface effects

Elemental analysis using a photoelectron spectrometer (X-ray photoelectron spectroscopy)

PTFE is heat-stable up to about 250 °C [17] and the frictional charging process may briefly generate such a high temperature that could alter the elemental composition of the PTFE surface. To check forth is effect, trace element analysis was performed using a photoelectron spectrometer (JPS-9200; Japan Electron, Japan). Identification of the elements and denaturation effects is possible using the relation between the photoelectron energy of the X-rays irradiating the sample surface and the number of photoelectrons observed.

Observation of surface roughness using scanning microscopy

To observe the surface roughness, an electrolyte emission electron microscope (JSM-6060 LV; JEOL Ltd, Japan) was used at 300,000× magnification.

Anticoagulation tests

Electret tubes with different surface potentials were prepared under different environmental conditions for testing the effect of relative humidity and room temperature on the friction charging method. The environmental conditions were as follows: 62–74% relative humidity, room temperature (20.4–22.4 °C), and an absolute humidity in the range of 11–14.7 g/m^3. The blood of a healthy adult male was introduced into a PTFE tube and stored at 36 °C for 14 days in an air-sealed state where air was completely blocked using PTFE stoppers (Fig. 1).

The samples were held for 14 days because commercially available non-cuffed catheters have a vascular indwelling period of 12 days when treated with urokinase immobilization and 10.6 days when untreated in clinical use [7]. After 14 days, the samples were washed with physiological saline and air-dried to be prepared for observation. The coagulation of the blood in the vial was observed using an upright microscope with 10× magnification (DMLB; Leica, Germany). The samples were imaged by flattening the inner surface of the PTFE electret tube under a glass plate. A single-lens digital camera (α7S, Sony, Japan) was used to capture the images. Surface potential measurements of the sample for anticoagulability observations were performed at the central part of the specimen and at a total of five locations in the 90° direction of the specimen. The average and the standard deviation values were calculated. We performed sterilization of PTFE tubes and stoppers using ethanol (70%) drying.

The platelet aggregation state was confirmed with May-Grünwald Giemsa staining (immersion method) [18]. Blood was collected with the approval of the Tokyo Institute of Technology Ethics Committee.

Results

Surface potential

The manufacturing environment was assumed to have a relative humidity of 26–68% and temperature of 20.6–27.7 °C (room temperature), which were similar to the environment of most of the hospitals' facilities [19]. In addition to the relative humidity, the absolute humidity was also obtained from the following equation [20, 21]:

$$C = \frac{217p}{T + 273.15}$$

$$P = \mathrm{Psa}\frac{h}{100}$$

$$\mathrm{Psa} = 6.1078 \exp\left[\frac{17.2694T}{T + 237.3}\right]$$

where T is the temperature (°C), p is the air's water vapor pressure (hPa), Psa is the saturated water vapor pressure (hPa) at room temperature, C is the absolute humidity (g/m^3), and h is the relative humidity (%).

Figure 2 shows the relation between the averaged surface potential and the relative humidity of ten negatively charged PTFE tubes. Figure 3 plots the relation between the averaged surface potential and absolute humidity. The surface potential is proportional to the relative humidity and absolute humidity. The effect of absolute humidity is more closely correlated with the surface potentials. The absolute humidity was calculated from the temperature and humidity at the time of production. Next, we used a charge-distribution toner, as shown in Table 1. Because the toner turned red, showing negative charging on the entire

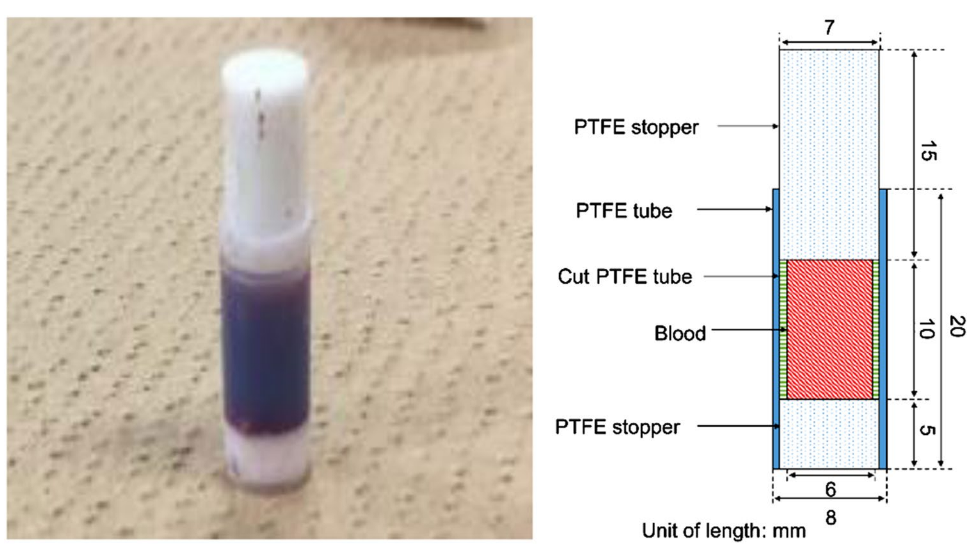


Fig. 1 Cross section of the tube with a blood sample

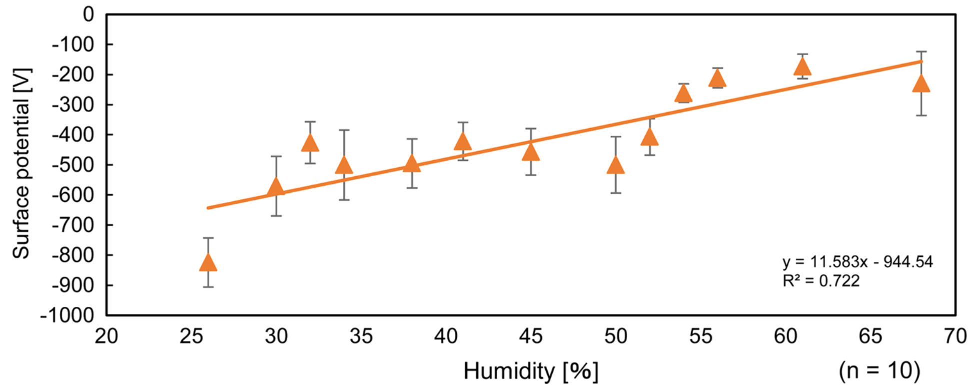


Fig. 2 Relative humidity versus surface potential

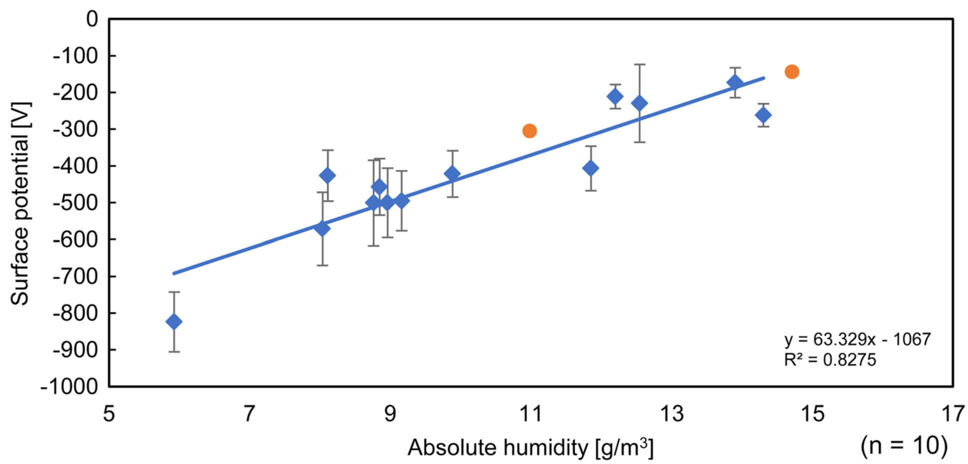


Fig. 3 Absolute humidity versus surface potential

inner surface and the inner surface was charged uniformly. We did not use any anticoagulant to completely avoid the influence of the anticoagulant. In other words, we aimed to evaluate the antithrombotic effect of the PTFE electret directly. Folded it with blood immediately after drawing the blood and was able to evade blood clotting during experiment work.

In other words, we aimed to directly evaluate the antithrombotic effect of PTFE electret. Blood clotting during the experiment was avoided by directly injecting PTFE electret after drawing blood.

Elemental analysis using X-ray photoelectron spectroscopy

The photoelectron spectrometry results shown in Fig. 4 show that the surface contained elements of carbon and fluorine, which are the main constituents of PTFE. No denaturation was apparent between the control and the triboelectrically charged electret tubes. We confirmed the element denaturation of the PTFE surface by the heat generated by the friction electrostatic charge in the XPS device.

We were also able to confirm that there was no *C*, which was a main element of the PTFE and the denaturation of the chemical bond state of *F*.

We considered the heat generated by friction and the effect of friction on wounds. When PTFE becomes electret, the carbon and fluorine atoms of PTFE are not denatured.

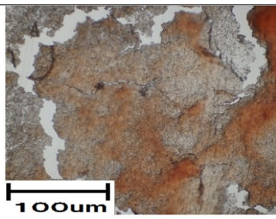
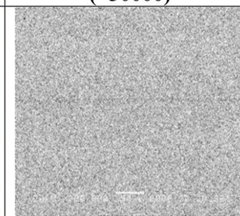
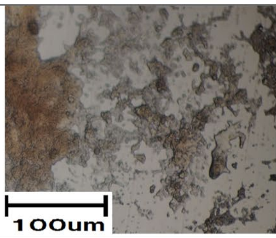
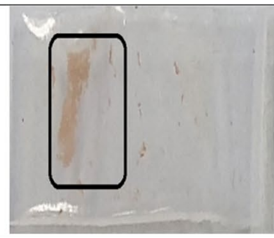
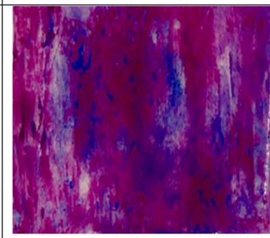
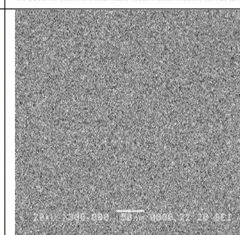
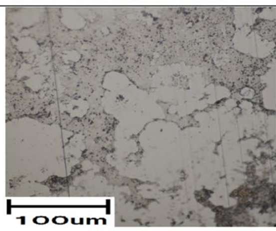
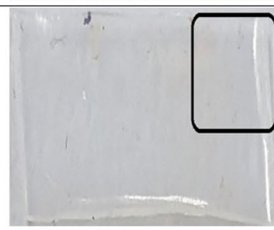
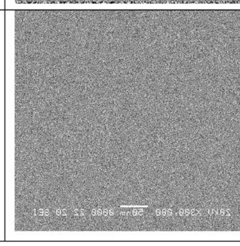
Observation of surface roughness using scanning microscopy

Scanning microscopy observations showed no difference between the control surface and the friction-treated surface. Triboelectric charging, therefore, causes no scratches that could host thrombi (Table 1).

Antithrombotic measurements

Observations of the different surface potentials' anticoagulation performance are shown in Table 1. The PTFE tube was charged in the friction zone and the thrombus status attached to the inner surface in different surface potential environment was compared.

Table 1 Surface potential, PTFE inner surface analysis, and clot adhesion observation

Surface potential	State of tube surface	Observation position	Charged distribution map	Sample surface electron microscope analysis (×30000)
Control tube: -4.2 ± 14.6V				
Electret tube A: -144.4 ± 131.7V				
Electret tube B: -305.4 ± 211.9V				

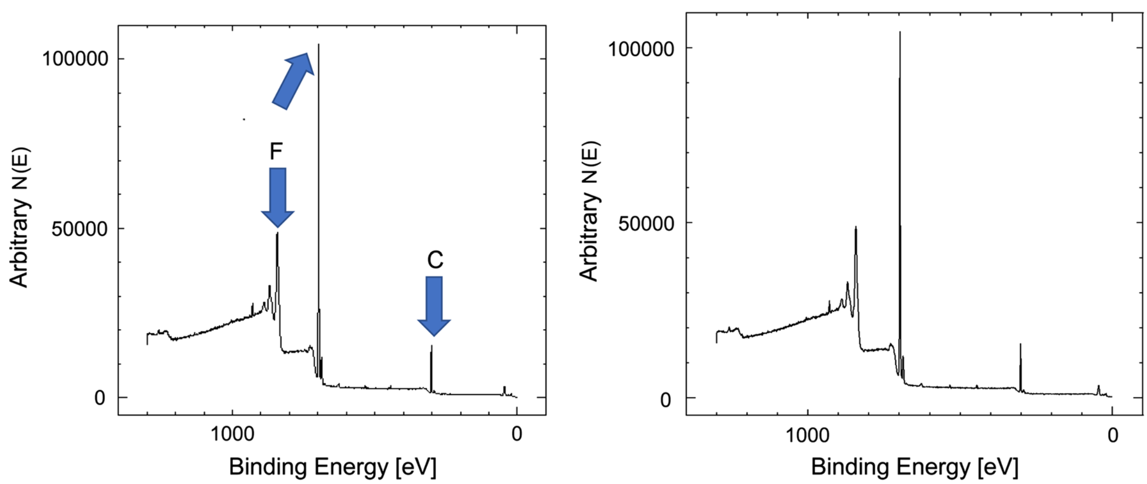


Fig. 4 Elemental analysis of control and treated surfaces using X-ray photoelectron spectroscopy

The clotting tendency was observed with an upright microscope. We found that the surface potential correlated directly with the anticoagulation performance. The relation between the average initial potential and the absolute humidity is as follows: electret A (− 144.4 V: 14.7 g/m^3), electret B (− 305.4 V: 11 g/m^3), and control (average initial potential: − 4.2 V). In Fig. 3, the two samples are labeled A and B. The correlation between the average initial potential and absolute humidity was found to be somewhat strong.

Discussion

The surface potential at which the highest antithrombotic activity was noted was − 305.4 V. At this potential, PTFE can become electret under absolute humidity that may be present in clinical environment. The typical use of "humidity" refers to the relative humidity, which is the percentage of actual steam pressure to the saturated steam pressure at the same temperature. Absolute humidity, conversely, provides a quantitative indication of how much water vapor is contained in the atmosphere and can be calculated from temperature and humidity [22]. Figures 2 and 3 show that the absolute humidity is more directly correlated with the surface potential than the relative humidity is. The electrical resistance of the material surface varies greatly with adsorbed water, explaining this effect [23]. The layer of adsorbed water molecules on the solid surface changes the work function of the surface and increases its conductivity, which affects the triboelectric charging characteristics. The PTFE that we used in this study has adsorbed water covering 0.001% or less of the surface [16], but Gibson argued that polymeric materials with even less water adsorption will lead to a large difference in charge quantity due to humidity [24]. When humidity changes, the adsorbed moisture content of the sample surface and the moisture content inside the sample also change [25]. When humidity increases, the electrical resistance on the surface or inside the sample decreases, so electric charges leak from the surface, decreasing the surface potential. Since electrical resistance increases at low humidity, triboelectric charging is more effective. Conversely, the surface is easier to charge as the temperature increases and discharging occurs more quickly [26].

In addition, denaturation caused by frictional heating is a concern. The spectrometry results showed no difference between the control and the treated samples (Fig. 4). This indicates that the frictional heating did not exceed 250 °C [20]. The scanning microscopy results showed no difference between the control surface and the electret surface, so triboelectric charging caused no surface irregularities that may have contributed to the anticoagulation effect.

Regarding the degree of anticoagulation, Akaike [27] argued that platelet activity is suppressed by electrostatic repulsion. However, as shown in Table 1, erythrocytes adhere to the surface along with fibrin. On the other hand, on the surface with a potential of −305.4 V, little platelet aggregation occurred and few fibrin networks formed. The negative charge on the contact surface suppressed platelet activity via electrostatic repulsion. Therefore, the relation between the negative surface potential and platelet inhibition was confirmed using the method developed by Lowkis [28]. During the release of platelets, which occurs after the adsorption of plasma proteins on the surface of foreign substances, platelet clot formation following prolonged contact with blood (several minutes) has been previously reported. Conversely, the Hageman factor is also activated by following contact with the surface of foreign substances; moreover, a series of solidifications by the endogenous system are sequentially activated to transform fibrinogen into insoluble fibrin that wraps around the platelet or a red blood cell and forms a clot [29]. PTFE, which forms a high hydrophobicity electret, has reduced surface adhesion to fibrin [30]. In addition, antiplatelet cohesion was confirmed by Giemsa's staining of such platelets. Thus, we were able to confirm the appearance of negative-charge PTFE electret not only when we controlled platelet activity but also when the extremely high hydrophobic PTFE surface restrained protein adsorption, such as fibrin adsorption. When blood comes in contact with a foreign substance, fibrinogen is converted to fibrin and a clot is formed, which includes a parcel comprising a platelet or a red blood cell [29]. In addition, highly hydrophobic PTFE prevents protein adhesion [30]. Therefore, platelet activity restraint by the negative charge and fibrin adhesion restraint by high hydrophobicity bestowed the antithrombotic nature to PTFE electret.

Hence, we conclude that triboelectric charging is effective in inducing antithrombotic properties in a long narrow tube. Furthermore, the frictional electrification method can be used to charge the inner surface of a cylinder almost uniformly, and the charge can be applied immediately before the material is used in a clinical environment. In addition, using a PTFE tube and a round glass bar, antithrombotic treatment can be applied in a sterile manner.

In this study, PTFE tubes were tested, but using friction charging with a double-lumen vascular catheter material should also be effective. Triboelectric charging is useful because it can quickly impart a nearly uniform negative charge-distribution on the inner wall of a tube with a very simple technique. Considering the temperature and humidity, typical in medical facilities, PTFE tubes can be treated with a high negative potential just before being used in a clinical setting. However, for cases in which the appropriate temperature and humidity conditions are not maintained, the amount of rubbing may need to be adjusted in order to ensure effective triboelectric charging. This detailed analysis would be studied in our future work. In the tests conducted, we examined the antithrombotic effect with blood in a stationary state, but the effect should also be tested in a fluid-flow condition using the Chandler loop method [31]. Hence, with this testing we have planned in our future work to develop an antithrombotic catheter.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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