A chair-side plasma treatment system for rapidly enhancing the surface hydrophilicity of titanium dental implants in clinical operations

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Abstract

\textbf{Purpose:} In order to promote osseointegration and shorten the healing time after dental implant operations, this study was conducted to develop a chair-side plasma treatment system in which Ti implants were used as a coaxial internal electrode to rapidly enhance their surface hydrophilicity.

\textbf{Methods:} Surface hydrophilicity was evaluated by measurement of the water contact angle and the defined wetting time. Changes in temperature and chemical composition were analyzed using infrared thermal imaging and X-ray photoelectron spectroscopy (XPS), respectively. The biocompatibility of the treated implants was examined in an animal experiment.

\textbf{Results:} A marked improvement of hydrophilicity was demonstrated by a decrease in the water contact angle of the treated implant to 0° and wetting of the whole surface within 3 s of water contact. The Ti implant hydrophilization mechanism was explained as a decrease in the degree of hydrocarbon contamination. The surface temperature of the treated implant was close to that of the human body, and good osseointegration was observed in the \textit{in vivo} experiment.

\textbf{Conclusion:} The plasma treatment system developed here is a promising chair-side procedure for rapidly enhancing the surface hydrophilicity of Ti implants in clinical operations without any need to consider the degradation of hydrophilicity caused by long-term storage.

Keywords: chair-side procedure, cold plasma, hydrophilic treatment, titanium dental implant

Introduction

In recent years, dental implants have been widely used to solve problems associated with missing teeth, facilitating a repairing effect equivalent to that of real teeth \cite{1,2}. Biocompatibility, chemical stability and resistance, favorable mechanical properties and reasonable machinability are all important factors for dental implant materials, but some metals such as stainless steel may cause adverse tissue reactions leading to a low success rate due to their poor corrosion resistance, whereas ceramic materials such as aluminum alloys \cite{13}, stainless steel \cite{14}, titanium alloys \cite{15} and polymers \cite{16} to enhance their surface hydrophilicity and adsorption properties. Furthermore, as a modification technology that modifies the surface to only a few nanometers, Chu \cite{17} has demonstrated that CAP can alter the surface biological properties of biomaterials without any change in bulk properties such as strength and inertness.

Ultraviolet irradiation \cite{7} and plasma treatment \cite{12} are typical examples of simpler treatment methods that do not alter the surface topography of implants. However, ultraviolet irradiation usually requires a long irradiation time, making hydrophilic treatment in clinical operations impracticable. In comparison, as an electrically neutral and ionized gas close to room temperature, cold atmospheric plasma (CAP) is a more rapid treatment modality, and has been widely used for surface modification of materials such as aluminum alloys \cite{13}, stainless steel \cite{14}, titanium alloys \cite{15} and polymers \cite{16} to enhance their surface hydrophilicity and adsorption properties. Furthermore, as a modification technology that modifies the surface to only a few nanometers, Chu \cite{17} has demonstrated that CAP can alter the surface biological properties of biomaterials without any change in bulk properties such as strength and inertness. Duske and Lee et al. \cite{12,18,19} have utilized the plasma jet technique to treat Ti discs for about 2 min and proved that this yields not only excellent surface hydrophilicity but also superior antibacterial ability. More importantly, by culturing MG-63 human osteoblasts \textit{in vitro}, Duske et al. \cite{18} have demonstrated that the spreading behavior of the cells on treated titanium discs is dramatically improved, with an increase in the cell-occupied area of up to 57-86\% in comparison with untreated Ti discs. In addition, Naujokat and Guastaldi et al. \cite{8,20}, employing miniature pigs and beagle dogs, respectively, have proved that Ti implants after plasma jet treatment can promote bone formation \textit{in vivo}, characterized by a slightly higher degree of bone-to-implant contact (BIC) and a significantly higher level of bone area fraction occupancy (BAFO) relative to untreated implants. Hence plasma treatment appears to be a promising way to convert normal implants to hydrophilic implants in clinical operations, because improved hydrophilicity can be obtained in a short time without any need to consider the degradation of hydrophilicity caused by long-term storage. However, due to the screw shape of the implant surface, as shown in Fig. 1(b), plasma in the form of a jet makes it difficult to treat a whole implant surface simultaneously, requiring practitioners to keep adjusting the relative position of the implant to the plasma jet manually. Such a relatively complex and uncontrollable treatment process would result in heterogeneity of the treatment effect. Consequently, treatment with a plasma jet is not the most ideal modality for use as a chair-side procedure in clinical operations. Taking into account the high conductivity of titanium alloy, a Ti implant can be employed directly as a coaxial internal electrode to generate cold plasma, submerging the whole implant and facilitating rapid hydrophilic treatment.

Here, the dielectric barrier discharge (DBD) needs to be adopted by inserting dielectric materials such as quartz between the internal and external electrodes to ensure a uniform discharge.
generate the CAP. Argon was used as the primary working gas to generate the CAP as it is low-cost and easy to ionize; a slight amount of oxygen was also added to produce oxygen-containing groups, which can further enhance the hydrophilicity and the antibacterial properties of the Ti implant. The wettability of the treated implants was then characterized by measuring the water contact angle and the defined wetting time. Clinical effectiveness and safety were verified by detecting the osseointegration state. Moreover, the chemical composition of the implant surface was analyzed by X-rayphotoelectron spectroscopy (XPS) to further explore the hydrophilization mechanism of the plasma treatment. The surface temperature of the treated implants was also measured by infrared thermal imaging to ensure clinical safety. Finally, it was demonstrated that the coaxial DBD plasma treatment system was able to rapidly enhance the surface hydrophilicity of the Ti dental implants at a temperature close to that of the human body.

Materials and Methods

Plasma treatment system

Figure 1(a) shows a schematic diagram of the coaxial DBD plasma treatment system, including the AC source, collet, implant, quartz tube, copper tube, and working gas. By adjusting the input current (220 V, 50 Hz), the AC source was able to provide an alternating voltage of several kilovolts to ionize the working gas at room temperature.

In order to respond to the rotary shape feature of the Ti implant, the latter was used as the coaxial internal electrode to conduct the DBD. The generated CAP was able to treat the whole implant surface simultaneously. As shown in Fig. 1(a), the implant was mounted on a metal collet, which was fixed by a fastening bolt and connected to the output of the AC source. The implant and the collet both served as the internal electrode. A quartz tube with an internal diameter of 8 mm and an external diameter of 10 mm acted as a dielectric barrier to avoid any arc discharge that could damage the implant surface. As the external electrode, a copper tube with an internal diameter of 10 mm and an external diameter of 12 mm covered the quartz tube and was connected to the output of the AC source. As the implant, collet, quartz tube, and copper tube were coaxial, the generated CAP was distributed uniformly in the space between the implant and the quartz tube, and the whole implant was submerged.

The system used argon as the primary gas and oxygen as the additional gas, the flowrates being precisely controlled by two mass flow controllers (MFC). Generally, the introduction of the oxygen-containing polar groups not only enhances the surface hydrophilicity of the implant but also enhances its antibacterial properties [15,21,22]. The gas mixture accessed the quartz tube via a helical route to match the screw shape of the Ti implant and to maximize the area of contact between the reactive radicals and the implant surface. Table 1 summarizes the basic parameters employed in this study.

Materials and hydrophilization procedures

The commercial Ti implant with a blast surface was used for this study (grade IV, WeiHai Wego Jericom Biomaterials Co., Ltd., Weihai, P. R. China). The mechanical properties of the implant were ascertained from the product description (modulus 104 GPa, ultimate tensile strength 550 MPa, yield strength 483 MPa, elongation 15%, density 4.5 g/cc). The shape of the implant is shown in Fig. 1(b). Two flat cutting edges at the tip were used to detect the water contact angle, and a cylindric carrier at the end of the implant allowed it to be clamped by the collet. The length and diameter of the implant were 7 mm and 3 mm, respectively.

To conduct the plasma treatment, the following operation steps were carried out. First, the implant was placed on the collet using sterilized hemostatic forceps, the collet was tightened, and the treatment chamber was closed manually. Next, using the touch panel of the system, the treatment parameters were set, including the treatment time (7-75 s), the current of the AC source (0.13-0.21 A), the argon flow rate (1-5 SLM), and the oxygen content (0-2%). Finally, the power of the AC source was turned on, and the implant was submerged in the generated CAP until the desired treatment time had elapsed. After the treatment, the chamber was opened and the collet was released manually. The implant was then removed using sterilized hemostatic forceps for further measurements or procedures.

Detection and analysis

Wetting property
To determine the change in the implant surface hydrophilicity after plasma treatment, the water contact angles of the same implant before and after the treatment were measured using a contact angle goniometer (PT-705B, Dong Guan Precise Test Equipment Co., Ltd., Dongguan, P. R. China). The measurements were conducted immediately after the plasma treatment, allowing the effect of storage time on the results to be ignored. Due to the screw shape of the implant surface, the measurement position was selected in a small flat area of the cutting edge, and a water drop volume of only 0.5 μL was used.

Also, as shown in Fig. 2, hydrophilic implants are able to draw water and the whole implant surface becomes wet immediately when the tip touches the water surface, whereas untreated implants do not exhibit this property. Therefore, the period from touching the water surface until complete wetting was achieved was defined as the surface wetting time of the implant, which allows the hydrophilicity of the implant to be further evaluated using different treatment parameters. A total of 23 specimens were divided into five experimental groups, corresponding to five treatment parameter variables (treatment time, AC source current, argon flow rate, oxygen content, storage time). Except for the group in which the treatment time was varied (seven specimens), each of the other three groups included five specimens, and each experimental group had one common basic treatment parameter set, as listed in Table 1. Video recordings of the surface wetting process of each implant were taken. The surface wetting time was then calculated by counting the video frames (30 frames being equivalent to 1 s). The videos were taken immediately after the plasma treatment, allowing the effect of storage time on the results to be ignored. Each experiment using different treatment parameters was repeated 6 times (n = 6) and a total of 138 specimens were assessed, the data being expressed as means and standard deviations.
w/v chloral hydrate 
dog was euthanatized with a lethal injection of 30 
performed using the standard protocol. After 4 weeks of implantation, the 
were placed in the mandible, respectively. All drilling procedures were 
were then extracted. After 3 months of healing, one treated Ti implant 
kg) and Zoletil (0.3 mg/kg). The mandibular second to third premolars 
A 1-year-old beagle dog weighing approximately 10 kg was used in this 
SIRB-D-2021-003) conducted under the ARRIVE (Animals in Research: 
- Diseases & National Clinical Research Center for Oral Diseases (WCH 
Scientific).

Surface chemical composition
To further explore the hydrophilization mechanism of the plasma treatment, 
changes in the chemical composition of the implant surface were 
analyzed by X-ray photoelectron spectroscopy (XPS, ESCALAB 250Xi, 
Thermo Fisher Scientific, Waltham, MA, USA). Four treated implants with 
different treatment times and one untreated implant were placed in steril-
ized sample bags and then subjected to XPS measurement, to reduce the 
effect of storage on the results as far as possible. Here the detection depth 
did not exceed 10 nm. The survey spectra of the implant surface and the 
corresponding high-resolution spectra of C1s, O1s and Ti2p were analyzed 
by X-ray photoelectron spectroscopy (XPS, ESCALAB 250Xi, Thermo Fisher Scientific).

In vivo animal experiments
The research protocol was approved by the State Key Laboratory of Oral 
Diseases & National Clinical Research Center for Oral Diseases (WCHR- 
SIRB-D-2021-003) conducted under the ARRIVE (Animals in Research: 
Reporting In Vivo Experiments) guidelines. All experiments were carried 
out in accordance with institutional and national animal care guidelines. 
A 1-year-old beagle dog weighing approximately 10 kg was used in this 
work. For surgery, the dog was anesthetized with Sumianxin II (0.04 mL/ 
kg) and Zoletil (0.3 mg/kg). The mandibular second to third premolars 
were then extracted. After 3 months of healing, one treated Ti implant 
with the treatment parameters listed in Table 1 and one untreated 
implant were placed in the mandible, respectively. All drilling procedures were 
performed using the standard protocol. After 4 weeks of implantation, the 
dog was euthanatized with a lethal injection of 30% w/v chloral hydrate 
solution, and the mandible specimen was fixed in 4% paraformaldehyde. 
To detect the newly formed bone around the implant, the sample was 
scanned using micro-CT (Scano Medical AG, Basserdorf, Switzerland). 
The scanning parameters were set at 90 kV and 200 μA with an exposure 
time of 500 ms and a resolution of 15 μm. Cross-sectional images were 
then taken (Amira 6, Thermo Fisher Scientific).

Statistical analysis
To evaluate the statistical power and effect size, power analysis was con-
ducted using the G*Power version 3.1.9.2 software package (program, 
concept and design by Franz Faul, Kiel University, Germany. Freely avail-
able Windows application software) [23]. The type of power analysis was 
selected as sensitivity, with a significance level α of 0.05 and a statistical 
power (1-β) of 0.8. With treatment time as the variable, the number of 
groups was 7, the sample size was 42 (n = 6), and the calculated effect size 
was 0.62; when other treatment parameters were used as the variable, the 
number of groups was 5, the sample size was 30 (n = 6), and the calculated 
effect size was 0.69.

All statistical analyses were conducted using Origin 2019b software 
(OriginLab Corporation, Northampton, MA, USA). The results of Levene’s test showed that the data collected did not satisfy homogeneity of 
variance (P < 0.05). To evaluate the effect of treatment time, the AC source 
current, the argon flow rate, the oxygen content, and the storage time on the 
wetting time and surface temperature, Kruskal-Wallis ANOVA (analysis of 
variance), which is a non-parametric test method, was performed. Dunn’s 
test was used as a post-hoc analysis for multiple comparisons. P < 0.05 was 
set as the level of significance.

Results
Wetting property
Figure 4 shows the changes in the water contact angle for the untreated 
and treated implants. It can be seen that the water contact angle of the 
untreated implant exceeded 102°, whereas the treated implant became wet 
instantly at the moment of contact with the water drop. Because the water 
was rapidly absorbed onto the threaded implant surface, the very small 
water contact angle could not be detected. Thus it was deduced that the Ti 
implant had obtained great surface hydrophilicity as a result of the plasma 
treatment and that the water contact angle was almost 0°. Han et al. [15] 
reported that the water contact angle of a Ti disc surface was also close to 
0° after hydrophilic treatment lasting 20 s using an atmospheric plasma jet. 
Consequently, irrespective of the Ti disc or Ti implant, it seems difficult to
distinguish the effects of treatment merely by measuring the water contact angle when different treatment parameters are employed.

To clarify the effectiveness of the coaxial DBD plasma treatment for rendering hydrophilicity, the surface wetting time was employed as a quantitative variable. Figure 5(a) shows the variation in the surface wetting time of implants with treatment time when other treatment parameters were set as basic parameters listed in Table 1. It can be seen that the implant was completely wetted as long as the treatment time was as long as 7 s, but a wetting time of 7.8 ± 2.1 s was required. When the treatment time was increased to 30 s, the wetting time required decreased to 2.7 ± 0.4 s, which was significantly shorter than that after treatment for 7 s (P = 0.029). However, no significant differences in the wetting time was observed when the treatment time exceeded 30 s. In other words, any further increase in the treatment time did not significantly reduce the wetting time. This suggests that the surface hydrophilicity of the implant appeared to peak after coaxial DBD plasma treatment for 30 s. Certainly, the hydrophilicity of a Ti implant surface is known to inevitably degrade under general storage exposed to air [11]. As shown in Fig. 5(b), for Ti implants subjected to the various parameters in Table 1, the required wetting time increased with the storage time. As the storage time increased from 0 to 2 h, the wetting time required also increased significantly from 2.7 ± 0.4 s to about 5.7 ± 0.1 s (P < 0.01). Any further increase in the storage time resulted in a slight increase in the mean wetting time, but not to a significant degree. After storage for more than 12 h, the implant would no longer be wetted completely. This suggests that the hydrophilicity induced by the plasma treatment system would also degrade with increased storage time. Additionally, it can be seen that a long wetting time was always accompanied by large standard deviations, suggesting that the stability of the measured result decreased along with the decrease of hydrophilicity.

Surface temperature

To examine the optimal balance between the temperature safety and wettablility of Ti implants during chair-side plasma treatment, the maximum temperature and wetting time of the treated implants were plotted as a function of various parameters. As shown in Fig. 6, as the treatment time increased from 7 s to 75 s, the temperature of the implant increased slowly from 39.9 ± 0.8°C to 55.3 ± 0.9°C (P < 0.01). An increase in the current of the AC source from 0.13 A to 0.21 A resulted in a sharp rise in the implant temperature from 39.0 ± 2.6°C to 98.2 ± 2.5°C (P < 0.01). Once the current exceeded 0.15 A, the implant temperature was difficult to maintain below 60°C. This was because a more powerful input current releases more heat, while a long treatment time allows the implant to absorb enough heat until a thermal equilibrium is reached [24]. On the other hand, an increase in the argon flow rate from 1 SLM to 5 SLM lowered the temperature of the implant from 58.7 ± 2.9°C to 45.1 ± 2.1°C (P < 0.01) due to promotion of heat exchange with the outside environment. Furthermore, addition of oxygen from 0% to 2.0% also caused a slight decline in the implant temperature from 50.9 ± 1.4°C to 42.6 ± 1.1°C (P < 0.01) because ionization of oxygen requires consumption of extra plasma energy. More importantly, the wetting time was dependent only on the treatment time (P < 0.01) and was not affected by the input current of the AC source (P = 0.06), the argon flow rate (P = 0.71), or the oxygen content (P = 0.1), perhaps indicating that the implant surface was able to fully react with the plasma as long as the plasma was generated, irrespective of the plasma state. Therefore,
selecting an AC current not exceeding 0.15 A, an argon flow rate of 3 SLM and an oxygen content of 2% for hydrophilization for about 30 s yielded a highly hydrophilic implant at a temperature close to that of the human body.

Changes in surface chemical composition
In general, excited atoms and active radicals in a plasma treatment system can increase the surface energy of a Ti implant and change its surface chemical composition [14]. To explore the hydrophilization mechanism and chemical safety of plasma treatment, changes in the chemical composition of the implant surface during the treatment process were characterized by XPS. Figure 7(a) shows the XPS spectra of Ti implants after they had been treated for different times. It can be seen that the type of element on the implant surface after treatment had no significant impact. The peaks of C1s at 284.8 eV, Ti2p at 458.5 eV, and O1s at 530.4 eV were clearly evident, and the plasma treatment did not introduce any harmful elements. Figure 7(b-d) show the high-resolution spectra of C1s, O1s, and Ti2p, respectively. After treatment, or as the treatment time increased, the peak intensity of elements may change according to changes in the chemical composition. By integrating the corresponding high-resolution spectra, the atomic ratios of carbon, oxygen, and titanium of the implant surface were calculated. As shown in Fig. 8, carbon and oxygen were the main components on the implant surface within a depth of 10 nm. The titanium content, which could be regarded as a constant, was far less than that of carbon and oxygen. For the untreated implant, the C1s and O1s contents were roughly 45%. When the plasma treatment lasted for 7 s, the C1s and O1s contents showed no significant change. After treatment for 30 s, the C1s content decreased to about 35%. In contrast, the O1s content showed a slight increase relative to the fluctuation in the Ti2p content. These results indicate a reduction of carbon-containing compounds and introduction of more oxygen-containing groups during plasma treatment.

The Ti2p spectrum with a double-peak structure at 458.5 eV and 464.5 eV appeared to confirm the presence of TiO2 [25]. The C1s spectrum was divisible into three components, including a C-C/C-H peak at 284.8 eV, a C-O peak at 286.4 eV, and an O-C=O peak at 288.4 eV, suggesting the presence of hydrocarbon contamination [26]. This could be expressed as CxHyOz, in which the C-C/C-H peak at 284.8 eV was identified as the hydrocarbon, whereas the C-O-C peak at 286.4 eV and the O-C=O peak at 288.4 eV represented oxygen-containing functional groups such as ether and carboxyl [27]. It can be seen in Fig. 9 that the proportion of the three

![Fig. 7 XPS analysis of the Ti implant surface after different treatment time. Survey spectra (a), and high-resolution spectra of carbon (b), oxygen (c), titanium (d)](image)

![Fig. 8 The atomic percentages of carbon, oxygen and titanium on the implant surface after different treatment times](image)

![Fig. 9 Area ratios of carbon-related bond energy from XPS spectra of the implant surface after different treatment times. Inset shows the peak fitting curve of C-C/H at 284.8 eV, C-O at 286.4 eV, and O-C=O at 288.4 eV.](image)
voltage not exceeding 20 V, the coaxial DBD plasma treatment system can
object [31]. Comparing with a plasma jet that provides only a low floating
depends on the potential difference between the plasma and the treated
Ti implant surface can result in the desorption of carbon contamination
active radicals [31,32]. Whether accelerated ion bombardment of the
physical sputtering of ions and chemical reactivity of oxygen-containing
results have confirmed that the improved hydrophilicity of an implant was
achieved using this coaxial DBD plasma treatment system by conducting
hydrocarbon polymer material such as polyethylene could also obtain great hydrophilicity after plasma treatment.
%
the C-C/C-H peak was always a dominator and fluctuated between 73%
and 79%. This suggests that the composition of the residual C,H,O, com-
main factor for hydrophilicity enhancement, whereas Chen and Steen et al. [26,29,30] considered that the introduction of oxygen-
containing polar groups is the main factor for hydrophilicity enhancement. Specifically,
Williams and Lee et al. [14,19] considered that removal of hydrocarbon contamination would change the composition of the residual carbon contamination.
[32]. However, neither physical sputtering of ions nor the chemical reac-
tion should also be recognized, where the active O atoms generated
by the plasma break the C-C and C-O bonds of the C,H,O, compound
and form more C=O bonds, and ultimately volatile products such as CO2.
[32]. However, neither physical sputtering of ions nor the chemical reaction
would change the composition of the residual carbon contamination.
Therefore, the XPS results showed a decrease in the C1s content (Fig. 8)
but relatively constant levels of the C-C/C-H, C-O-C, and O-C=O peaks
(Fig. 9) after the plasma treatment. Here, removal of the C,H,O, compound
would have led to a decrease in the O1s content, but in fact it increased slightly after treatment (Fig. 8). This is because the oxygen content at the
Ti implant surface existed mainly in the form of metal oxides, and the
oxygen-containing plasma would have further oxidized this even if the
untreated implant already had an oxide layer [33,34], which could also
enhance the hydrophilicity [26,29,30].
The Ti implant subjected to the coaxial DBD plasma treatment had shown high hydrophilicity characterized by a water contact angle close to
0° and a wetting time of 3 s. For the ultraviolet irradiation method proposed by Neobiotech, implants need a wetting time of at least 20 s [Young-goo H
et al., Kr Patent 101972122B1, Apr 24, 2019]. In comparison to ultraviolet irradiation, plasma treatment confers better hydrophilicity on Ti implants.
In addition, the coaxial DBD plasma treatment system can fully immerse a
Ti implant in a plasma environment, and the entire implant can be treated
homogeneously in a few seconds. While a plasma jet requires repeated
scanning over the implant and a few minutes are needed to complete the
hydrophilization [15,18]. Thus, the coaxial DBD plasma treatment system
has a fast response and is easy to operate in a clinical setting.
Long-term storage is often considered to be detrimental to the hydro-
philicity of an implant surface. Adhesion of external contamination and a
decline in surface energy are responsible for the degradation of implant
surface hydrophilicity under normal storage conditions. However, Lu et al.
[11] have pointed out that degradation of hydrophilicity cannot be avoided
even if an implant is stored in a sealed container. Thus the use of the
coaxial DBD plasma treatment system for chair-side treatment in clinical
operations would be an optimal way to avoid hydrophilicity degradation.
Dental implant osseointegration is susceptible to heat-induced damage.
Once the temperature of bone tissue exceeds 60°C for 1 min, the quality
of osseointegration drops sharply [35]. For a chair-side plasma treatment
system, it is necessary to keep the maximum temperature of an implant
below 60°C. The present experimental results suggest that an implant with
high hydrophilicity can be obtained at a temperature close to that of the
human body merely by setting the current at less than 0.15 A, with an
argon flow rate of 3 SLM, an oxygen content of 2%, and a treatment time
of 30 s. Chemical safety should also be taken into account during plasma
treatment because the introduction of harmful elements may cause corri-

![Fig. 10 Transverse micro CT image at the center of the treated and untreated implants after 4 weeks of implantation in vivo. Treatment parameters are detailed in Table 1.](image-url)
sion and release ions into the surrounding tissue, with unknown biological consequences [36]. The present XPS results indicated that the treated implant surface had no discernible harmful elements that might have been introduced by the coaxial DBD plasma treatment system. Therefore, the system should be safe enough for use on Ti dental implants in clinical operations.

In conclusion, it has been shown that plasma treatment of implants for less than 30 s can confer high hydrophilicity, as evidenced by a water contact angle close to 0° and a wetting time of 3 s. Enhancement of Ti implant surface hydrophilicity during plasma treatment is mainly attributable to a decrease of hydrocarbon contamination and the introduction of a denser oxide layer. The removal of hydrocarbon contamination is achieved by physical sputtering of ions and chemical reactivity of oxygen-containing active radicals. Furthermore, the temperature of the treated implant can be controlled to approximate that of the human body, and there is no introduction of any harmful elements during the plasma treatment. More importantly, improvement of osseointegration after 4 weeks of implantation was observed in vivo, which further verified the effectiveness and safety of the plasma treatment. Consequently, coaxial DBD plasma treatment appears to be a promising strategy for rapidly enhancing the surface hydrophilicity of dental implants in clinical operations without any need to consider the degradation of hydrophilicity caused by long-term storage.

Overall, the coaxial DBD plasma treatment system described here shows the excellent ability for improving the hydrophilicity of implant surfaces, and is effective and safe for clinical application. As a chair-side procedure, it should solve the problems related to the degradation of implant hydrophilicity by allowing practitioners to conduct hydrophilic treatment in clinical operations. To further verify its clinical effectiveness, more biological experiments will be conducted in the next study.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (51875372, 52005353), the Strategic Cooperation Research Project between Sichuan University and Yibin City (2019CDYB-7), the Technological innovation research and development project of Chengdu Science and Technology Bureau (2019-YF05-01328-SN), and the Miaozi Project in Science and Technology Innovation Program of Sichuan Province (20-YCG045).

Conflict of interest
The authors have no conflicts of interest to declare.

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