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Light-induced bone cement-philic titanium surface

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Abstract The survival of cemented endosseous implants can be improved by enhancing the bond between the implant and the cement. We hypothesized that the light-inducible generation of super-hydrophilicity of titanium positively affects its bone cement-philicity and bone cement–titanium bonding. Commercially pure titanium disks with machined surface and acid-etched micro roughened surfaces were prepared. Ultra-violet (UV) light treatment (0.1 mW/cm^2 UVA and 0.03 mW/cm^2 UVB for 48 h) created a super-hydrophilic surface for both surface types. The area of poly-methyl methacrylate (PMMA)-based bone cement spread increased by 30% and 20% on the light-treated machined titanium and acid-etched titanium surfaces, respectively, compared to the matched untreated ones. The contact angle of the bone cement decreased significantly after the light treatment, confirming the enhanced wettability of bone cement by the light treatment. Interfacial tensile stress between the bone cement material and titanium was increased 100% for the machined surface and 50% for the acid-etched surface by light treatment. Interfacial shear stress measured by a push-out test of titanium rods also revealed a 40% increase for the machined surface and 25% increase for the acid-etched surface. In conclusion, the pre-UV light treatment of titanium enhances the wettability and bonding strength of poly-methyl-methacrylate-based bone cement.

Introduction

Cement fixation provides excellent stability of titanium implants and is an essential tool in current orthopedic implant treatments as represented by total hip arthroplasty [1–3]. Acrylic resin-based bone cements, primarily consisting of a solid part of a prepolymerized poly-methyl methacrylate (PMMA) and a liquid part of methyl methacrylate (MMA), are the most frequently used materials for this purpose. Debonding the cement–metallic implant interface has been implicated as a major cause of failure initiation [1, 4–7]. Micromotion of implants after debonding accelerates the interfacial wear and eventually results in the higher chance of early loosening at the cement–implant interface [5, 6]. It is biomechanically and clinically proven that the survival of cemented implants can be improved by enhancing the bond between the implant and the cement [8–10].

To improve the mechanical properties of the bone cement, various modification techniques have been attempted [11]. Cement containing PMMA fibers in its matrix form seems to increase fracture resistance [12, 13]. The addition of bioglass or bio-ceramic to resin-based cements helps to increase the mechanical strength of the PMMA cements [14, 15]. These modifications alter the chemical properties, as well as the mechanical properties, of the materials and require additional characterization of their biological compatibility. More importantly, while these approaches may enhance the intrinsic mechanical properties of the bone cement, they, however, may be less effective in reinforcing the cement–metal interface. From a cementing technique standpoint, a

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precoating with a thin layer of PMMA around the implant stem [9, 10, 16–19] and applying the cement at the earlier polymerization stage [20] seem to be useful to increase the cement–implant interfacial strength. However, the improvement may not be necessarily significant enough to increase the fixation of implants [21].

The ultraviolet (UV) light generation of a highly amphiphilic (both hydrophilic and oleolphilic) titanium surface was first introduced in 1997 [22]. The unique character of this surface is ascribed to the physicochemical changes that occur during UV light treatment. A first possible explanation for this phenomenon is that the generation of amphiphilicity is due to the removal of surface contaminants by light-excited hydroxyl groups (hydroxyl radicals) on the titanium surface. Titanium absorbs the organic impurities, such as carbon and hydrocarbons, constantly from the atmosphere, water and cleaning liquid [23–25]. Secondly, the light treatment may create surface oxygen vacancies at bridging sites, resulting in the conversion of relevant Ti^{4+} sites to Ti^{3+} sites which are favorable for dissociative water absorption [22].

We hypothesized that the light-inducible changes in wettabilities (hydrophilicity, oleophilicity) of titanium positively affects its bone cement-philicity and bone cement–titanium bonding. Herein we present a method to enhance bone cement–titanium interfacial strength without modifying bone cement materials. The UV light-treated titanium has been demonstrated to show higher bone cement wettability and stronger bone cement–titanium interfacial strength than the untreated control. The effects of the light treatment were tested for different titanium surface topographies; a machined, relatively smooth surface and an acid-etched, relatively rough surface.

Materials and methods

Titanium samples, surface analysis and ultraviolet (UV) light treatment

Two surface types of commercially pure grade 2 titanium were prepared for cylindrical rods (1 mm in diameter and 2 mm in length) and disks (20 mm in diameter and 1.5 mm in thickness). One had a machined surface, turned by a lathe. The other was acid-etched with H_2SO_4 and HCl. Titanium disks and rods were treated with 0.1 mW/cm^2 UVA and 0.03 mW/cm^2 UVB for 48 h with air ventilation. The surfaces of the titanium samples were examined by scanning electron microscopy (SEM) (JSM-5900LV, Joel Ltd., Tokyo, Japan) and an energy dispersive X-ray spectrometer (EDX) (JSM-5900LV, Joel Ltd., Tokyo, Japan). In addition, machined titanium alloy disks were prepared from 6Al–4V titanium ELI alloy.

Hydrophilicity and bone cement-philicity tests

Contact angle and spread area of distilled water (hydrophilicity test) and bone cement (bone cement-philicity test) were evaluated on the titanium surfaces with or without UV light pretreatment. Ten microlitre of distilled water was gently placed on the titanium disks and digitally photographed immediately. The spread area was measured as the area of the drop in the top view using a digital analyzer (Image Pro Plus, Media Cybernetics, Silver Spring, MD). The contact angle θ was obtained by the equation: $\theta = 2\tan^{-1}(2h/d)$, where h and d are the height and diameter of the drop in the side view [26]. Bone cement was prepared by mixing 18.88 g of liquid and 20 g of cement powder for 20 s, which was double the liquid ratio of the manufacturer's instruction (Endurance MV, DePuy Orthopaedics, Warsaw, IN). Ten microlitre of the mixed cement was gently placed on the titanium disks at a time span of 80 s from the commencement of mixing. Three independent disks were tested.

Tensile test for titanium–bone cement interface

Bone cement was mixed (18.88 g liquid and 20 g powder) for 20 s, and 500 µL of the mixed cement was placed onto the titanium disks for natural spread. After allowing the cement to polymerize at 37 °C for 24 h, the premade methyl methacrylate acrylic column (10 mm in diameter) was attached to the polymerized cement using another fresh mixture of cement. The cement-column assembly was further polymerized for 24 h. The testing machine (Instron 5544 electro-mechanical testing system, Instron, Canton, MA) equipped with a 2,000 N load cell was used to detach the bone cement from the titanium surface. The column was vertically pulled at a crosshead speed of 1 mm/min, and the interfacial tensile stress was determined by calculating the peak of the load–displacement curve divided by the spread area of bone cement. Six independent disks were tested.

Titanium rod push-out test

This method was originally developed and established to assess the biomechanical strength of bone–implant integration, and the details are described elsewhere [27]. We applied this method to assess the titanium–bone cement interfacial shear stress. The cylindrical rods (1 mm in diameter and 2 mm in length) with or without light treatment and an acrylic block were prepared. The acrylic block had pre-made holes of 2 mm in diameter and of 2 mm in height. The bone cement was prepared by mixing the powder and liquid as instructed by the manufacturer

(18.88 g liquid and 40 g powder). At 80 s, the titanium rods pasted with the prepared bone cement were placed into the holes of the acrylic block with the top surface level and flushed with the resin block top surface. The bone cement was polymerized in a 37 °C for 24 h. The Instron machine loaded the titanium rod vertically downward at a crosshead speed of 1 mm/min, and the interfacial shear stress defined as the peak load of load–displacement curve divided by the area of the sidewall of the titanium rod was measured. Six independent titanium samples were tested.

Morphology of cement–titanium interface after tensile test

To examine the titanium–cement detachment behavior, titanium surfaces after the tensile test were examined by scanning electron microscopy (SEM) (JSM-5900LV, Joel Ltd., Tokyo, Japan).

Statistical analysis

Two-way ANOVA was used to assess the effect of titanium surface roughness and UV light treatment on the bone cement wettability variables, titanium–cement tensile and shear stress variables. Bonferroni multiple comparison was used as a post-hoc test to examine differences between the untreated control and light-treated titanium surfaces; <0.05 was considered statistically significant.

Results

Surface characteristics of titanium

High and low magnification SEM images showed concentrically turned ridges on the machined surface (Fig. 1a, c), whereas the acid-etched surface was uniformly roughened (Fig. 1b). High magnification SEM revealed the micron-level roughness with defined peaks and valleys on the acid-etched surface (Fig. 1d). EDX showed that both machined and acid-etched titanium showed only an elemental peak of titanium, and no differences were found before and after the UV light treatment.

Super-hydrophilic titanium surfaces induced by light treatment

The spread area of 10 µL water drop dramatically increased on the UV light-treated machined (13 times) and acid-etched (30 times) surfaces compared to the respective untreated surfaces (Fig. 2a, b). The contact angle of water before treatment, which was approximately 70° and 90° for the machined and acid-etched surfaces, respectively, plummeted to 0.0 ± 0.0° after light treatment, indicating the emergence of super-hydrophilic surfaces (Fig. 2c).

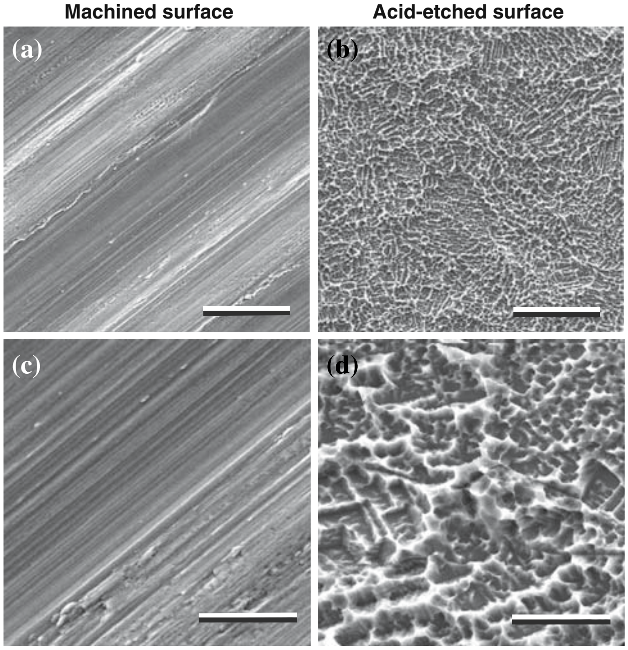

Fig. 1 Surface morphology of titanium surfaces used in this study. Scanning electron micrographs of the machined surface (**a**, **c**) and acid-etched surface (**b**, **d**). Bar = 20 µm in (**a**) and (**b**), 5 µm in (**c**) and (**d**)

Increased bone cement wettability on light-treated titanium

The area of bone cement spread increased by 30% and 20 % on the light-treated machined titanium and acid-etched titanium surfaces compared to the matched untreated ones ($p < 0.01$) (Fig. 3a, b). The contact angle of the bone cement decreased significantly after the light treatment ($p < 0.01$) (Fig. 3c), confirming the enhanced wettability of bone cement by the light treatment.

Increased bone cement–titanium tensile stress by light treatment

Two way ANOVA showed that the cement–titanium interfacial stress measured by the tensile test is approximately two times higher for the acid-etched surface than for the machined surface ($p < 0.01$) (Fig. 4). The tensile stress was increased by the light-treatment of titanium approximately 1.8-fold for machined surface ($p < 0.01$,

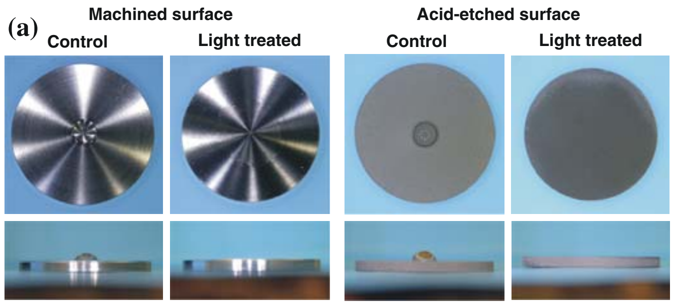

Fig. 2 An ultraviolet (UV) light-induced dramatic changes of wettability of titanium surfaces having two different surface topographies; machined and acid-etched surfaces. The hydrophilicity was evaluated by the spread area (the top views of titanium disks) (**a**, **b**) and the contact angle (the side views of titanium disks) (**a**, **c**) of 10 μL droplets of distilled water. Note that the contact angle is 0.0 ± 0.0° (super-hydrophilic) after UV treatment on the both surface topographies. Data are shown as the mean ± SD ($n = 3$). * Statistically significant between the UV treated titanium and non-treated control, $p < 0.01$

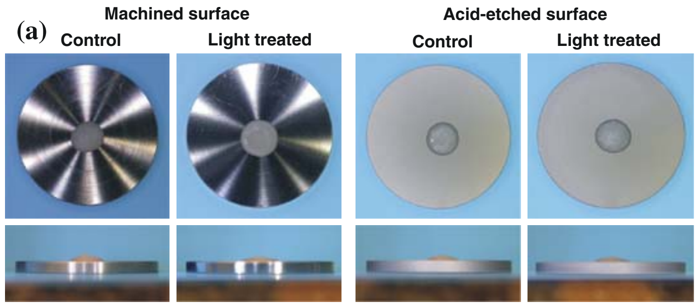

Fig. 3 An ultraviolet (UV) light-induced change of bone cement wettability of titanium. The bone cement-philicity was evaluated by the spread area (the top views of titanium disks) (**a**, **b**) and the contact angle (the side views of titanium disks) (**a**, **c**) of 10 μL droplets of the bone cement. Data are shown as the mean ± SD ($n = 3$).* Statistically significant between the UV treated titanium and non-treated control, $p < 0.01$

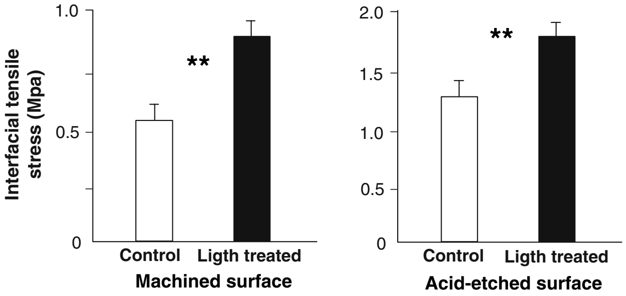

Fig. 4 Bone cement–titanium interfacial tensile stress measured of the machined and acid-etched titanium surfaces with or without light treatment. Data are shown as the mean ± SD ($n = 6$). Statistically significant between the light-treated implants and untreated control, ** $p < 0.01$

Bonferroni) and 1.5 times for the acid-etched surface ($p < 0.01$).

Increased bone cement–titanium shear stress by light treatment

The cement–titanium shear stress measured by the push-out test was increased by the light-treatment of titanium implants by 40% for the machined surface ($p < 0.05$) and 25% for the acid-etched surface ($p < 0.01$) (Fig. 5). The shear stress was higher for the acid-etched surfaces than for the machined surfaces even after the light treatment ($p < 0.01$).

Morphology of dissociated cement–titanium interface

The untreated control machined surfaces showed surface images identical to their original parallel-stripe morphology and there was no remaining cement component after the bone cement tensile test (Fig. 6a, e). In contrast, some areas of the light-treated machined surface exhibited a thin layer of cement remnant along the parallel ridge pattern (Fig. 6b, f).

Although difficult to recognize in the low magnification image (Fig. 6c), high magnification images revealed that the post-tensile test acid-etched surface retained the cement material, mostly tangled along the roughened peaks (black arrow heads in Fig. 6g) and filled into the micron-level pit structures (white arrow heads in Fig. 6g). The light-treated acid-etched surface was extensively covered by a relatively

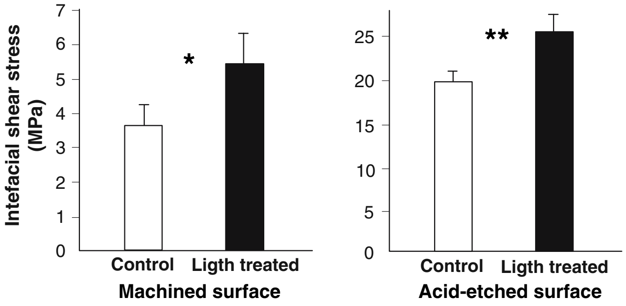

Fig. 5 Interfacial shear stress measured by push-out test of the machined and acid-etched titanium rods with or without light treatment. Data are shown as the mean ± SD ($n = 6$). Statistically significant between the light-treated and untreated control, ** $p < 0.01$, * $p < 0.05$

thick cement material after the tensile test (Fig. 6d). The cement remnant varied in thickness, and a sheared appearance can be seen in some areas. Most of the cement remnant appeared to be attached firmly to the titanium surface, although a portion of the remnant began to slough off from the titanium surface (black arrows in Fig. 6h). Cement materials that were sheared but still engaged into the pits are clearly seen on the light-treated acid-etched surface (white arrow head in Fig. 6h).

Increased bone cement wettability on light-treated titanium alloy

The light-induced cement wettability was also found on the titanium alloy. The area of bone cement spread increased by 50% on the light-treated machined titanium alloy (Fig. 7) compared to the untreated one. The contact angle of the bone cement decreased accordingly after the light treatment.

Discussion

This is the first study, to our knowledge, demonstrating the potential, therapeutic usefulness of light-treated titanium in endosseous implant treatments. We hypothesized that the light-induced superhydrophilic status positively affects cement wettability and eventually its bonding strength to the titanium surface. Although the improved wettability of bone cement was not as remarkable as seen in water in terms of the spread area or contact angle, probably due to the much higher viscosity, the improved wettability of cement was sufficient enough to enhance the cement–titanium interfacial strength by up to two times, supporting our hypothesis. The method is novel and significant in that the effect is obtained without changing the surface roughness of titanium, the chemistry of bone cement or any cementing procedure. Further, the successful results for the different surface topographies of titanium suggest that the utility of this discovery may be universal for various surface types of titanium-containing implant materials.

Considerable efforts have been made to mechanically improve the cement–metal interface as a potential, triggering factor for implant loosening and failure. Proven improvements to the interfacial strength include the use of roughened implant surfaces and clinical techniques when applying bone cement [28–30]. For instance, grit-blasted rough surfaces and chemically treated surfaces with porosity generate strong interfacial shear strength over the polished, smooth surface [18, 19, 31]. However, a number of clinical studies raised notable concerns associated with the use of roughened implant surfaces, revealing a detrimental aspect of an increased rate of implant loosening and osteolysis [32, 33]. The release of implant surface structure and cement component wear debris into the peri-implant tissue has been invariably observed in histological sections

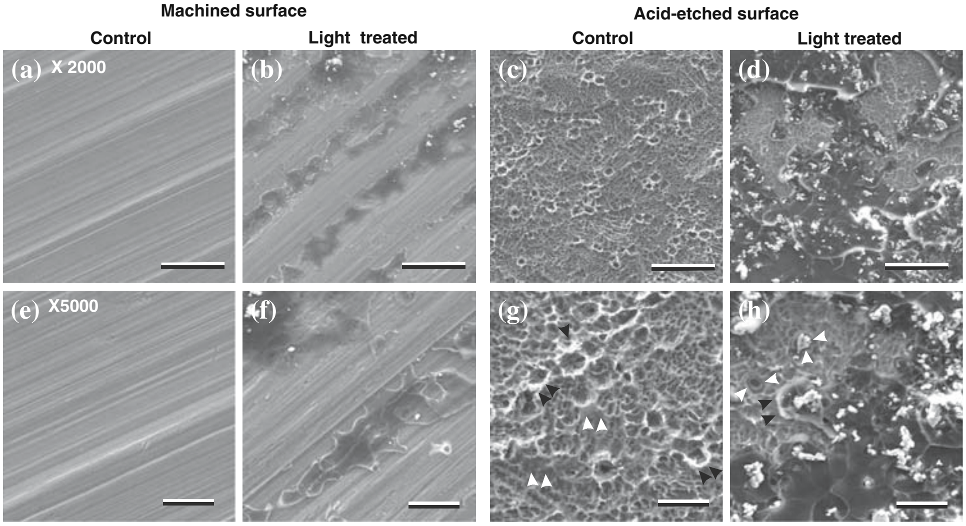

Fig. 6 Morphology of detached cement–titanium interfaces. Scanning electron micrographs of the untreated machined surface (**a**, **e**), UV light-treated machined surfaces (**b**, **f**), untreated acid-etched surface (**c**, **g**), and UV light-treated acid-etched surfaces (**d**, **h**) after performing the bone cement tensile test. Bar = 20 μm in the (**a**)–(**d**), 4 μm in (**e**–**h**)

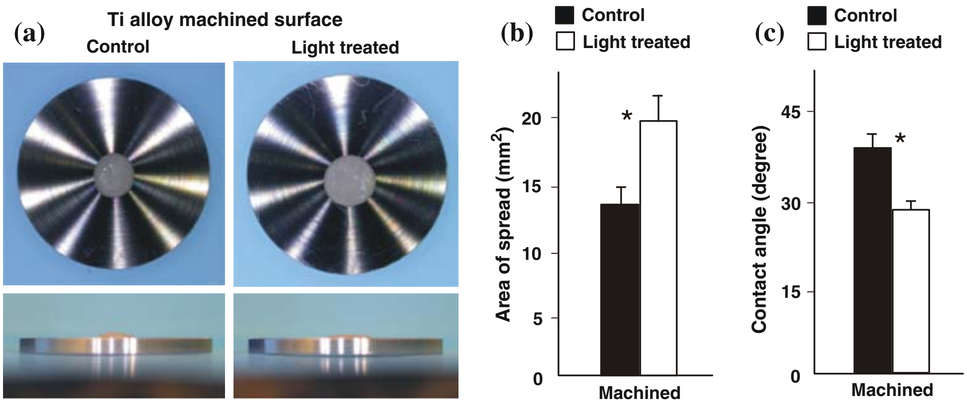

Fig. 7 An ultraviolet (UV) light-induced change of bone cement wettability on titanium alloy. The bone cement-philicity was evaluated by the spread area (the top views of titanium disks) (**a**, **b**) and the contact angle (the side views of titanium disks) (**a**, **c**) of 10 µL droplets of the bone cement. Data are shown as the mean ± SD ($n = 3$). * Statistically significant between the UV treated titanium and non-treated control, $p < 0.01$

[34, 35] and suggested to be a cause [7, 33]. Therefore, smooth surfaces that allow the subsidence and micromotion of an implant without damaging the cement mantle and titanium surface may be secure [36]. The presented physicochemical activation, that has effectively boosted the interfacial strength of the cement-machined smooth surface, is meaningful and should be utilized in the clinical environment.

We used the increased ratio of liquid for the cement-philicity test and tensile test. With the normal powder and liquid ratio, the mixed bone cement was not fluid enough to spread on the titanium disks. The bone cement mixture could have been pasted onto the titanium disks by an instrument for the tensile test. However, we considered a concern that the bone cement may not be placed in a reproducible manner by an instrument, in terms of the area and intimacy of the cement material, and decided to let the bone cement spread without artificial force. Instead, the results of the tensile test were confirmed by shear tests using the bone cement with a regular powder/liquid ratio. In this shear study, we utilized the titanium rods whose sizes were applicable to in vivo rat model we established [27]. The titanium implants with or without UV treatment may be placed with bone cement into the rat femur in the future. The biomechanical strength of implant retention will be assessed and compared to the present in vitro outcome for consistency. In this study, we only examined an immediate effect of light treatment of titanium on the cement–titanium interfacial stress. The long-term fatigue test, the effectiveness of the light treatment on the bone cement interface under the cyclically loaded and/or wet conditions are needed to be examined in future studies [37, 38].

Implant placement involves an unavoidable formation of interfacial porosity and microgap at the interfacial cement. It is interpreted being as the result of incomplete coverage of bone cement, and cement shrinkage away from the implant surface toward the outer surface of the cement. An experimental study showed that the gap between the cement and implant varies significantly, ranging from 0 to 16 µm, depending on the implant surface roughness, and that the gap formation can be minimized by PMMA cement precoating [18]. The degree of the gap formation corresponded to the clinically and post-mortem observed debonding of the interface [18]. There is a supporting report that showed that the porosity at the cement–implant interface may cause the fluid penetration and result in the lower interfacial strength [38]. Further, an in vitro biomechanical study demonstrated a close relationship between the time to cementation and cement–metal bonding strength [20]. Earlier cementation, before doughy the stage of the acrylic cement, resulted in higher tensile and shear strengths, particularly for the grit-blasted rough surface. Our SEM examination revealed that the light-treated titanium surfaces associated themselves with the bone cement remnant after the tensile test, suggesting the improved infiltration of cement material into the microstructure of the titanium surfaces. These documentations have confirmed a critical role of cement philicity, particularly the degree of intimate contact, onto the prosthetic material in determining the interfacial strength. It is known that increased roughness does not necessarily increase the interfacial strength of cement, since inherently high viscous cement does not infiltrate sufficiently into the surface roughness and rather augments additional air being trapped [18]. The light treatment may be particularly effective in solving this concern, as represented by the bone cement remnant interlocked into the detail of the acid-etched microroughness, vividly observed by SEM.

The light-induced superhydrophilicity is known to be obtained on various types of substrates containing titanium components [39, 40]. Also, this study demonstrated that the bone cement-philicity was increased on titanium alloy disks. Therefore, we may assume that the effectiveness of the present UV technique is promising on titanium alloys. The effect of light treatment on the creation of hydrophilicity of other implantable metals, such as chromium–cobalt alloy, has not been addressed previously or in the present study, and may be of immediate and great interest. The feasibility of light treatment technique also needs to be examined for its effectiveness on chemically modified titanium, such as ceramic coated titanium [41], hydroxyapatite coated titanium [42], and calcium phosphate coated titanium [43], since these surfaces have been regularly introduced into the field. Another crucial issue is that the future use of acrylic bone cement. The acrylic bone cement inherently limits the biocompatibility and long-term prediction of implants [44, 45]. There is a trend toward cement-free implantation to avoid bone cement complications, including the rate of immediate death post-cementation [44, 45]. Biological as well as the biomechanical aspects of bone cement need to be considered for better lifetime predictability of implant therapy.

In conclusion, UV light treatment of titanium enables more intimate contact and interlocking of bone cement to the titanium surfaces, resulting in the enhancement of cement–titanium interfacial strength. Given that there is no practical and effective way to improve the cement–metal interfacial mechanical properties other than cement precoating, this technique may be expected as a relatively simple and effective measure to improve cement-implant bonding strength in the near future for orthopedic implant therapy.

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