Success Rate, Healing Time, and Implant Stability of Photofunctionalized Dental Implants

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Purpose: *This is the first study to report the clinical outcomes of photofunctionalized dental implants.* ***Materials and Methods:*** *This retrospective study analyzed 95 consecutive patients who received 222 untreated implants and 70 patients who received 168 photofunctionalized implants over a follow-up period of 2.5 years. Photofunctionalization was performed by treating implants with UV light for 15 minutes using a photo device immediately before placement. The generation of superhydrophilicity and hemophilicity along with a substantial reduction in atomic percentage of surface carbon was confirmed after photofunctionalization. In both groups, 90% of the implants were placed in complex cases requiring staged or simultaneous site-development surgery. The implant stability was measured at implant placement and loading using the implant stability quotient (ISQ) values; then, the rate of implant stability development was evaluated by calculating the ISQ increase per month.* ***Results:*** *The healing time before functional loading was 3.2 months in photofunctionalized implants and 6.5 months in untreated implants. The success rate was 97.6% and 96.3% for photofunctionalized and untreated implants, respectively. The ISQ increase per month for photofunctionalized implants ranged from 2.0 to 8.7 depending on the ISQ at placement, and it was considerably higher than that of untreated implants reported in the literature ranging from –1.8 to 2.8. Photofunctionalization resulted in a more frequent use of implants of 10 mm or shorter length and an overall decrease in implant diameter.* ***Conclusions:*** *Within the limits of this retrospective study, despite the more frequent use of shorter and smaller-diameter implants, the use of photofunctionalization allowed for a faster loading protocol without compromising the success rate. The outcome was associated with an increased rate of implant stability development. The results suggest that photofunctionalization may provide a novel and practical avenue to further advance implant therapy.* Int J Oral Maxillofac Implants 2013;28:1261–1271. doi: 10.11607/jomi.3263

Key words: *hydrocarbon, superhydrophilic, super osseointegration, titanium, ultraviolet*

Ultraviolet (UV) light treatment of titanium implants has been reported to increase bone-to-implant contact (BIC) from 55% to a near maximum level of 98.2% in an animal model.[1–3] The increased BIC resulted in a threefold increase in the strength of bone-implant integration.[1–3] Moreover, the increased BIC is demonstrated to contribute to even distribution and reduced levels of mechanical stress in the peri-implant marginal bone.[4] The effectiveness of UV treatment in challenging conditions such as bone healing with short implants and a significant peri-implant gap has also been demonstrated.[5,6] The enhancement in osseointegration is attributed to the generation of superhydrophilicity, a significant decrease in surface hydrocarbons, and improvement in the electrostatic status of titanium surfaces after UV treatment.[1,7–9] These surface property changes were demonstrated to result in an increased recruitment, attachment, retention, proliferation, and overall phenotype of osteogenic cells.[1–3,7,8,10–12] The biological effects along with UV-enhanced surface properties are collectively defined as photofunctionalization of titanium implants.[2,3,7,13–15]

Despite establishment as a routine procedure, implant therapy still faces many challenges in application and treatment outcomes. The extended healing time required for osseointegration needs to be shortened to decrease patient morbidity and to accommodate the growing demands of modern implant therapy. Various

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Table 1 Patient Data

	Implants	Patients	Mean age (range)	Sex (female/male)
Untreated implants	222	95	52.7 ± 16.9 (20–76)	63/32
Photofunctionalized implants	168	70	55.6 ± 11.0 (22–78)	50/20

Fig 1 *(right)* The device used for photofunctionalization of dental implants (TheraBeam Affiny). Implant fixtures are placed on the sliding stage. The device performs an automatic program of 15-minute UV exposure.

pre-implant surgeries, including bone augmentation and sinus lift procedures, have proven useful for expanding the indications of implant therapy; however, the clinical outcomes of implant placement in such cases may not be as predictable as those in regular placement cases.[16,17] More rapid and complete establishment of bone–implant integration has been a persistent goal.

A crucial question exists: do the biologically and scientifically proven acceleration and enhancement of osseointegration by photofunctionalization actually contribute to current clinical implant dentistry? In this study, we retrospectively evaluated consecutive patient populations who received either untreated implants or photofunctionalized implants and analyzed the success rate, dimensions of implants, implant stability development, and healing time before loading.

MATERIALS AND METHODS

Patients

There were two patient groups (untreated implant and photofunctionalized implant groups) formulated from consecutive patients who visited the Nagisa Dental Clinic (Kanazawa, Japan) for implant therapy during 20 months from April 2009 through November 2010. Photofunctionalization was implemented in the clinic in February 2010, after which point all implants were photofunctionalized. The photofunctionalized implant group included 168 implants placed in 70 patients who visited the clinic after February 2010, whereas the untreated implant group included 222 implants placed in 95 patients who visited before February 2010. The demographic data for each group are presented in Table 1. Patients were included if they were at least 20 years old, compliant with oral health care instructions and necessary visits, and provided consent for documentation and public presentation of their clinical data. Patients with systemic conditions that could potentially affect bone and soft tissue healing such as osteoporosis, diabetes, or radiation treatment were excluded.

Clinical Procedure and Photofunctionalization of Implants

Implant therapy was proposed and performed in the same manner for the untreated and photofunctionalized implant groups. Following routine procedures for local anesthesia and full-thickness flap reflection, implants were placed with a torque of 25 to 45 Ncm per the manufacturer's instructions. The implants used in this study possessed a tapered root form and identical surface morphology (Osseotite Certain, Biomet 3i). Photofunctionalization was performed at chairside immediately before implantation (Fig 1) by treating the implants with UV light for 15 minutes using a photo device (TheraBeam Affiny, Ushio). The photofunctionalization-induced change in surface property from hydrophobic to superhydrophilic was confirmed prior to patient visits by examining several implants for their wettability with double-distilled water (Figs 2a and 2b). Photofunctionalization was also confirmed by observing blood spiraling up the implant immediately after it was in contact with the drilled site, as typically seen in Fig 2c. This hemophilicity was not observed for the untreated implants. Furthermore, the chemical composition of implant surfaces was evaluated by x-ray photoelectron spectroscopy (XPS) (ESCA3200, Shimadzu). The atomic ratio of carbon to titanium (C/Ti), which was 109% before photofunctionalization, decreased to 38% after photofunctionalization.

Implant Location and Proportion of Complex Cases

Neither the number of implants placed in each location nor the distribution between the maxilla and mandible was significantly different between the untreated and photofunctionalized implant groups. The most common implant location was the posterior mandible, followed by the posterior maxilla, anterior maxilla, and anterior mandible in both groups. The implants used in this study largely involved complex procedures with pre-implant or concomitant surgery in both groups. Implant placement in fresh extraction sockets, bone

Figs 2a to 2c *(a)* Hydrophobic implant surface before photofunctionalization with three droplets of 3 μL double-distilled water (total 9 μL) showing very limited area of water contact on implant surface. *(b)* Superhydrophilic surfaces were generated on implants after photofunctionalization, showing that 9 μL of water (three droplets of 3 μL) was sufficient to spread and cover the entire implant surface. *(c)* A highly hemophilic implant after photofunctionalization. A typical intraoral image of photofunctionalized implants after contact with an implant site. Note the dynamics of the blood spiraling up along the implant threads and reaching the coronal portion.

Table 2 Implant Data

	Overall implant length			Implant diameter		Complex cases	
	Mean (mm)	≤ 10 mm (%)	≥ 13 mm (%)	Mean (mm)	≥ 5 mm (%)	Implant length (mm)	Implant diameter (mm)
Untreated implants (n = 222)	12.04 ± 1.69	56 (25.2)	109 (49.1)	4.71 ± 0.75	123 (55.4)	12.20 ± 1.65	4.64 ± 0.73
Photofunctionalized implants (n = 168)	11.76 ± 1.69^{NS}	63 (37.5)	72 (42.9)	4.51 ± 0.71**	66 (39.3)	11.71 ± 1.30*	4.50 ± 0.76^{NS}

Statistically significant differences between untreated and photofunctionalized gropus: *P < .05, **P < .01, NS: not significant.

with simultaneous or staged guided bone regeneration (GBR) and/or simultaneous or staged sinus elevation was defined as complex cases, accounting for 84.2% and 91.7% implants in the untreated and photofunctionalized implant groups, respectively.

Implant Dimensions

The lengths and diameters of implants used are presented in Table 2. The use of implants 10 mm or shorter was more frequent in the photofunctionalized implant group (37.5%) than in the untreated implant group (25.2%). The implant diameter was significantly smaller in the photofunctionalized implant group than in the untreated implant group; implants 5 mm or wider in diameter were used less often in the photofunctionalized group. Implants used in complex cases were significantly shorter in the photofunctionalized implant group.

Implant Stability

Implant stability was evaluated by measuring the impant stability quotient (ISQ) at implant placement and commencement of functional loading using Osstell ISQ (Osstell). Furthermore, the rate at which implant stability was established was evaluated by calculating the ISQ increase per month, which was defined as [(ISQ at loading) – (ISQ at implant placement)]/(healing time before loading). Implant stability measurement was performed for all photofunctionalized implants. The average ISQ from four measurements (four different directions at the mesial, distal, buccal, and lingual surface of an implant) was used for further statistical analysis. The ISQ device was implemented in the clinic after photofunctionalization was introduced. Therefore, ISQ data were only available for photofunctionalized implants.

Implant Success

Implant success was evaluated according to the success criteria of Smith and Zarb[18] after follow-up periods of 2.5 to 3.5 years and 1.5 to 2.5 years after final restoration for the untreated and photofunctionalized implant groups, respectively. Implant failure was confirmed by the presence of significant mobility, radiographically confirmed failure of osseointegration or progressive disintegration, significant marginal bone loss, pain, inflammatory signs, and/or rapid and continuous decrease in ISQ values.

Potential Surgical Complications

Potential surgical complications were monitored, including duration and level of pain, bleeding, inflammatory reaction of tissues, improper or delayed wound healing, postoperative infection, damage to neighboring natural teeth, or postsurgical sensory disorders.

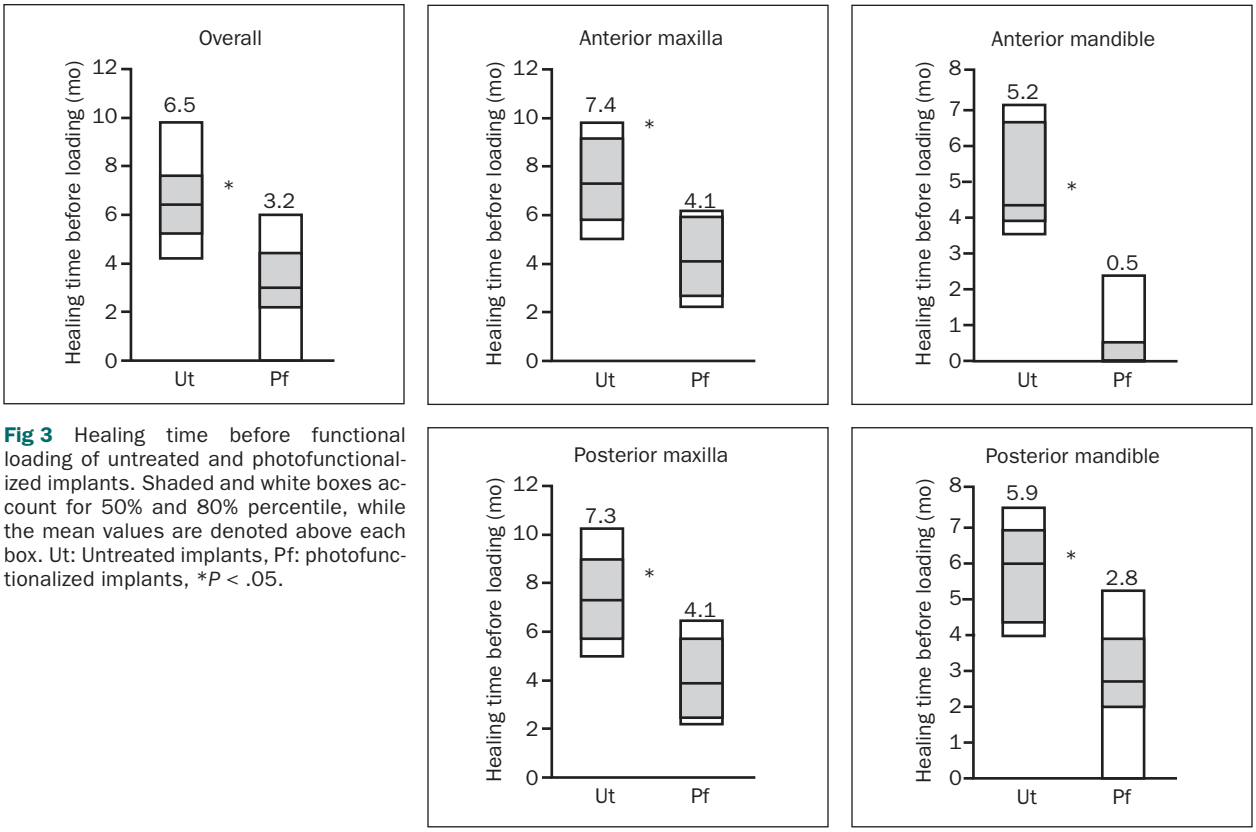

Fig 3 Healing time before functional loading of untreated and photofunctionalized implants. Shaded and white boxes account for 50% and 80% percentile, while the mean values are denoted above each box. Ut: Untreated implants, Pf: photofunctionalized implants, *$P < .05$.

Statistical Analysis

Differences in healing time between untreated and photofunctionalized implants were examined using the Mann-Whitney *U* test. Differences in implant length and diameter between the two groups and ISQ changes with time were examined by analysis of variance (ANOVA). A *P* value of < .05 was considered statistically significant.

RESULTS

Healing Time

The average healing time before functional loading was two-fold shorter for photofunctionalized implants than for untreated implants: untreated implants were loaded 6.5 months after placement while photofunctionalized implants were loaded 3.2 months after placement (Fig 3). A substantial reduction in healing time was consistently seen in all regions. A drastic decrease in the healing time in the anterior mandible was a result of a general reduction of healing and increased instances of immediate loading.

The distribution of healing times is plotted in Fig 4. The overall results showed that none of the untreated implants were immediately loaded, whereas 17% of photofunctionalized implants were immediately loaded. Taken together, 50% of the photofunctionalized implants were either loaded immediately or within a period of 3 months. None of the untreated implants were loaded during this early stage. Photofunctionalization resulted in a considerable decrease in the proportion of healing times greater than 6 months. Less than 10% of photofunctionalized implants and 50% of untreated implants were subjected to such long healing. Region-specific distribution of healing time revealed that 75% of photofunctionalized implants placed in the anterior mandible were immediately loaded. Early loading within 3 months was applied in 35%, 100%, 37%, and 54% of photofunctionalized implants in the anterior maxilla, anterior mandible, posterior maxilla, and posterior mandible, respectively.

Success Rate

The overall success rate for untreated implants was 96.3%. Eight out of 222 implants in seven patients failed. Seven out of the 8 implants were not integrated at second-stage surgery. One implant failed after provisionalization. The success rate for photofunctionalized implants was 97.6%. Four out of 168 implants failed. All

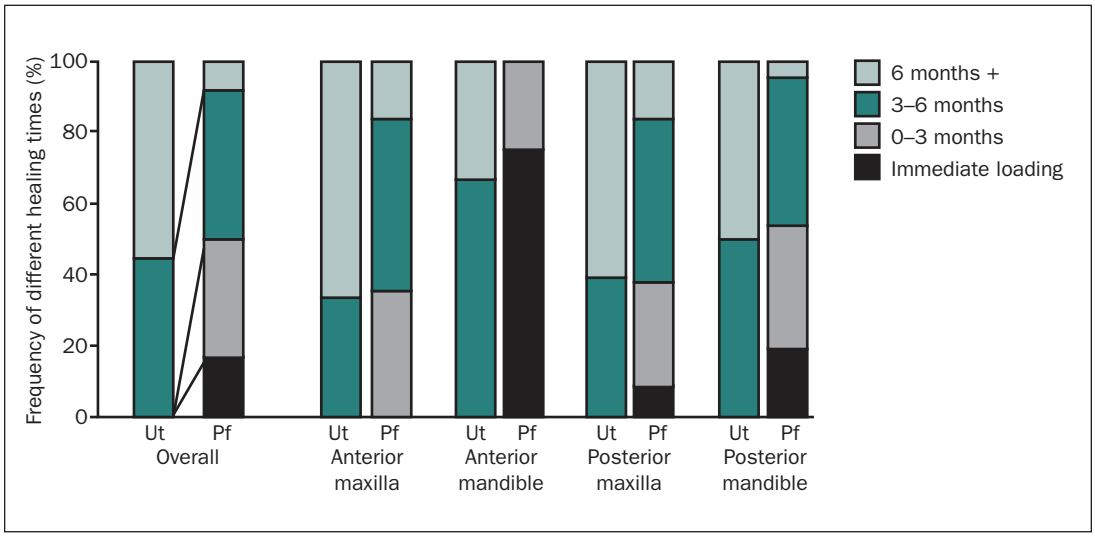

Fig 4 The distribution of specific healing times before functional loading of untreated and photofunctionalized implants. Ut: Untreated implants, Pf: photofunctionalized implants.

Table 3 ISQ Change and Increase for Photofunctionalized Implants

		ISQ		
Primary stability range	**Implants**	**At placement (ISQi)**	**At loading**	**Increase/m**
ISQi < 40	3	37.7 ± 2.3	63.0 ± 7.5**	4.6 ± 0.4
ISQi 40–49	8	47.6 ± 1.8	73.8 ± 8.6***	8.7 ± 4.1
ISQi 50–59	13	56.1 ± 2.7	66.8 ± 8.7***	2.6 ± 2.4
ISQi 60–69	18	66.5 ± 2.6	70.5 ± 12.4^{NS}	NA
ISQi 60–64	4	62.8 ± 1.5	74.0 ± 7.2*	2.0 ± 1.5
ISQi 65–69	14	67.6 ± 1.5	69.5 ± 13.5^{NS}	NA
ISQi 70–79	33	76.1 ± 1.9	72.4 ± 11.5^{NS}	NA
ISQi ≥ 80	24	82.7 ± 1.9	80.4 ± 6.1^{NS}	NA

ISQi 60–69 was subdivided into ISQi 60–64 and 65–59 groups to precisely determine threshold of significant change in ISQ at loading.
Statistically significant differences between time points; *P < .05; **P < .01; ***P < .001; NS: not significant.
ISQi: initial ISQ at implant placement; NA: not applicable.

failures were associated with early provisionalization within 3 months (1 implant placed in a fresh extraction socket, 2 in sinus lift sites, and 1 at a vertical GBR site). There was no disintegration observed before provisionalization. Therefore, the failure rate before functional loading was 3.15% for untreated implants and 0.0% for photofunctionalized implants. There was no late failure after the final prostheses were placed for both groups.

Implant Stability

Implant stability was evaluated by categorizing implants according to the range of initial ISQ (ISQi) at placement. First, implants were divided into six groups by a 10-point ISQi interval (Table 3). When the ISQi was lower than 60, the ISQ at loading increased significantly. The increase (a difference between implant placement and loading) ranged from 10.7 to 26.2 points and was more remarkable when the ISQi was low (Fig 5 and Table 3). When the ISQi was 60 or higher, the subsequent ISQ did not change significantly (Fig 5 and Table 3). To precisely determine the ISQi threshold that leads to a significant change at loading, "ISQi 60 to 69" group was subdivided into "ISQi 60 to 64" and "ISQi 65 to 69," as shown in Table 3. It was shown that when the ISQi was 60 to 64, the ISQ at loading was significantly increased from the level at placement, whereas the ISQi of 65 to 69 did not show a subsequent significant change. Furthermore, for the implants that showed a significant ISQ increase between placement and loading, the ISQ increase per month was calculated (Table 3). The ISQ increase per month was the highest at 8.7 ± 4.1 when the ISQi was 40 to 49.

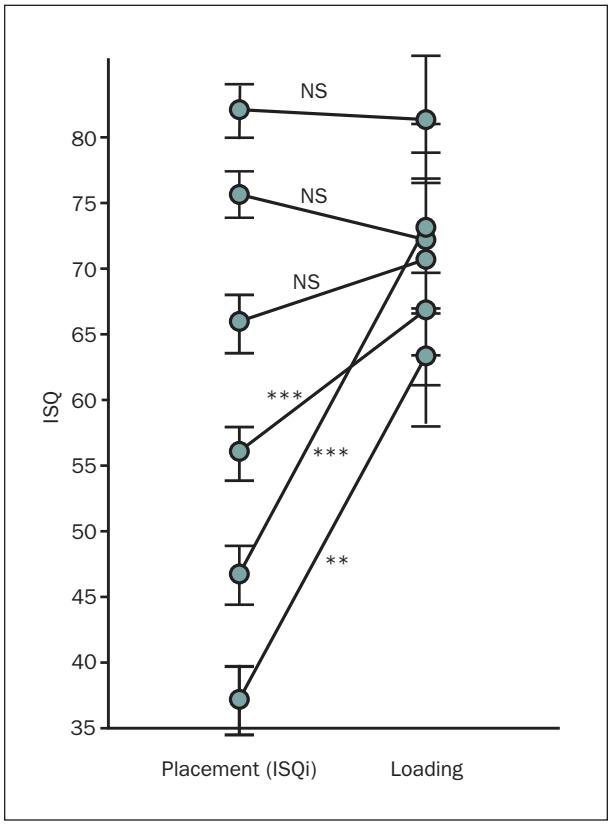

Fig 5 The ISQ values at implant placement and functional loading. Implants were divided into six groups depending on their initial ISQ at placement (ISQi). Mean and standard deviations are plotted for each group. Statistically significant differences were observed between the two time points. $^{**}P < .01$, $^{***}P < .001$. NS: not significant. See Table 3 regarding further determination of significant ISQ change in the ISQi 60 to 69 group.

Complications

Surgical complications were documented in association with 11 untreated implant placements: peri-implant infection observed with titanium (Ti) mesh exposure (3 implants), peri-implant infection with soft tissue dehiscence in a case of simultaneous GBR (1 implant), noninfectious Ti mesh exposure (5 implants), exposure of the cover screw (1 implant), and tentative and mild sensory disorder (1 implant).

Photofunctionalization, which takes 15 minutes, was initiated several minutes before anesthetizing the patients. By the time the drilling was complete, the photofunctionalized implants were ready for placement, which resulted in no delay or time loss during surgery. No surgical complication that required an extra procedure was documented in association with photofunctionalized implants. One implant was associated with a noninfectious minor Ti mesh exposure. The surgical complication rate was 4.95% (11 incidents/222 implants) for untreated implants and 0.59% (1 incident/168 implants) for photofunctionalized implants.

DISCUSSION

Implant placement in complex cases is considered to increase the risk of implant failure and requires a substantially longer healing time. In general, 6 months is required to secure osseointegration before loading in augmented bone.[19] Bone with multiple augmentation procedures such as a combination of vertical ridge augmentation and sinus lift may require an extended healing time of up to 13 months.[20] Implants placed in extraction sockets should be left unloaded for 4 months[21] or 5 to 6 months.[22] If horizontal and vertical peri-implant gap is anticipated in the socket, implant placement should take place after 5 months or more, followed by an additional healing time of 9 months or more for osseointegration.[23,24] In this study, successful osseointegration was demonstrated after an average healing time of 3.2 months using photofunctionalized implants, a majority of which were placed in bone with the above-mentioned challenging conditions.

Findings from animal studies may be helpful in understanding the high clinical performance of photofunctionalized implants in the present study. A rat study showed that implant placement without cortical bone support reduced the strength of osseointegration by 60%.[5] However, photofunctionalized implants placed in the same site achieved the strength of osseointegration equivalent to the implants with cortical support. The effect was explained by the robust osteogenesis initiating at the implant interface, which rapidly spread to the remote cortical bone. In contrast, osteogenesis around untreated implants was initiated at the surface of remote cortical bone and slowly approached the implant interface. More than 75% of implants in this study involved simultaneous GBR and fresh extraction sockets with a significant peri-implant gap. The successful result for these implants is well-supported by the previous animal study.

Another animal study addressed a potential disadvantage caused by the use of short implants and further determined whether photofunctionalization could mitigate this disadvantage.[6] In that study, implants with 40% shorter length resulted in a 50% or more decrease in the strength of osseointegration. However, when the short implants were photofunctionalized, the osseointegration strength doubled and this disadvantage of short implants was eliminated.[6] This was explained by increased bone coverage around photofunctionalized implants that offset the reduced surface area. Photofunctionalization is known to increase the percentage of bone-implant contact by nearly two times.[1] Most implants in the present study were placed in complex cases and had a limited area supported by native bone. The successful outcome for these implants may arise from the evidence of this animal study. More convincing is

the fact that photofunctionalization allowed for more frequent use of 10-mm or shorter implants, thus opening a new avenue of minimally invasive implant therapy even in challenging cases. Moreover, the average length and diameter were significantly smaller for the photofunctionalized implants than untreated implants. This study presents only results based on a retrospective study design, and the obtained differences were relatively small. The authors believe future studies with more controlled designs will address the clinical impact of these findings by identifying how short and narrow dental implants can be used with photofunctionalization to generate a load-bearing capacity high enough to tolerate specific bone conditions.

Measuring implant stability at placement, as well as the subsequent change during healing, provides useful information for monitoring the process of osseointegration, planning a loading protocol, and evaluating various conditions of osseointegration on the implant and host sides.[25–31] The use of ISQ values based on resonance frequency analysis has been extensively reported for its reasonable reliability and validity.[27,32–37] In addition to observing the expected progress of osseointegration, the timing of the stability decrease has been a focus in evaluating implant surfaces and determining loading protocols. ISQ values are sensitive enough to detect the stability decrease between weeks 1 and 8 after implant placement.[26,28,33,38–41] In this study, to ensure the reliability of ISQ data, the mean value obtained from four time measurements was used for statistical analyses.

The authors postulated that the evaluation of implant stability using ISQ values was more meaningful when the initial value at implant placement and the period of time required to reach the final value are considered. In this way, ISQ values could be standardized and allow for a comparison among implants with different healing times and different primary fixations. Therefore, in the present study, the ISQ change between the time of placement and functional loading was first calculated. Next, the ISQ change was divided by the time required before loading to obtain the ISQ increase per month and evaluate the rate of implant stability development. ISQ change between two time points has been presented as a useful parameter in many previous studies along with a description of when they were measured.[25,33,38,42,43] The ISQ increase per month was further calculated by dividing the ISQ change by time as an indicator for the rate of implant stability development.

The obtained data of implant stability change and ISQ increase per month strongly supported the high success rates of photofunctionalized implants, even with the accelerated loading protocol. In this study, ISQ data were only available for photofunctionalized implants, and therefore, the data were compared with untreated implants in the previous articles after a thorough literature search (Table 4). Because there is a general trend in the literature that implants with an initial ISQ of 70 or higher show no significant change during subsequent healing, the authors searched and listed papers that dealt with implants with an initial ISQ of less than 70.[22,25,26,33,38–40,43–48] There were two major findings from this search: *(1)* the ISQ increase between the first and second measurements for photofunctionalized implants, ranging from 10.7 to 26.2, was substantially greater than those in the literature, ranging from –5.0 to 4.6, and *(2)* the ISQ increase per month of photofunctionalized implants, ranging from 2.0 to 8.7, was notably higher than that reported in the literature, ranging from –1.8 to 2.8.

Several reports specifically examined ISQ changes under compromised bone conditions. The ISQ values for implants placed in fresh extraction sockets generally remains unchanged or slightly decreased, even after 6 to 12 months.[22,49] Implants placed in anterior maxilla sites augmented with graft material did not show a significant increase, even after sufficient healing.[43] Against the common understanding, the present study, which largely included compromised bone conditions, showed a significant ISQ increase, supporting the application and successful outcome of early loading within 3 months in a large number of cases.

Limited information is available regarding ISQ changes when their initial values are below 55. It is assumed that implant placement in such high-risk cases has been avoided because of low primary stability. According to the limited number of reports, implants placed in fresh extraction sockets with an initial ISQ of below 55 do not result in successful osseointegration.[22] Implants placed in the grafted anterior maxilla with an initial ISQ of approximately 50 to 55 showed a high failure rate of 35%.[43] In the present study, all photofunctionalized implants with an initial ISQ of below 50 exhibited successful osseointegration, implying the possible expansion of indications for implant therapy.

The failure rate before functional loading was 0% for the photofunctionalized implants, as opposed to 3.15% for the untreated implants, indicating that none of the photofunctionalized implants showed destructive changes in peri-implant bone during the initial healing stage. This may be of great importance in understanding another therapeutic advantage of photofunctionalization. The osteoconductive capability of Ti is known to correlate negatively with the amount of surface carbon on Ti surfaces.[1,9] Currently available commercial implants are unavoidably contaminated with hydrocarbons to a significant degree.[50–56] The average amount of surface carbon is 35% to 55%, and it varies significantly from less than 20% to more than

Table 4 Comparison of ISQ Changes in the Literature Between Implant Types

Implant surface	Placement conditions	ISQ		Healing period (mo)	ISQ increase per mo
		Initial (at placement)	Secondary§		
TiUnite[44] (Anodic oxidized)	Maxilla	63.3 ± 6.1	64.3 ± 5.3	3	0.33
TiUnite[43]	Anterior maxilla	58.5 ± 4.7	60.9 ± 4.3	6	0.4
	Grafted anterior maxilla	61.5 ± 9.0	60.2 ± 6.9	6	–0.2
TiUnite[45]	Grafted anterior maxilla	61.4 ± 5.1	61.0 ± 7.9	6	–0.1
TiUnite[46]	Maxilla	60.1 ± 3.6	62.8 ± 1.6	4	0.68
TiUnite[26] *	Primarily GBR and extraction sockets	68.0	63.0	3	–1.67
TiOblast[47] (sandblasted)	Maxilla	62.3 ± 5.1	63.9 ± 5.5	6	0.27
	Grafted maxilla	56.9 ± 4.7	58.2 ± 4.7	6	0.22
	Grafted maxilla	60.7 ± 6.1	61.4 ± 5.2	6	0.12
Not specified[22]	Fresh extraction socket maxilla	61.1 ± 1.1	63.9 ± 5.6	5.6	0.5
	Fresh extraction socket mandible	65.1 ± 2.6	64.0 ± 2.1	5.6	–0.2
SLA[25] (sandblasted and acid-etched)	Overall	57.4 ± 6.8	60.3 ± 6.1	3	0.9
	Maxilla	55.0 ± 6.8	57.9 ± 6.0	3	0.9
	Mandible	59.8 ± 6.7	63.9 ± 6.0	3	1.3
	Type I bone	62.8 ± 7.2	60.7 ± 3.6	3	–0.7
	Type II bone	56.9 ± 5.9	60.1 ± 5.8	3	1.1
	Type III bone	56.0 ± 7.8	60.6 ± 7.2	3	1.5
SLA[38] *	Maxilla	54.0	57.2	2.5	1.3
	Mandible	60.0	62.7	2.5	1.1
SLA[33] †	ISQi < 50	NA	NA	3	2.8
	ISQi 50–59	NA	NA	3	1.1
	ISQi 60–69	NA	NA	3	0.46
	ISQi 60–64	NA	NA	3	0.63
	ISQi 65–69	NA	NA	3	0.15
SLA[40]	Maxilla	55.4 ± 3.8	57.0 ± 2.8	1.5	1.06
	Mandible	65.5 ± 5.5	62.8 ± 5.4	1.5	–1.8
SLActive[40] (sandblasted and acid-etched; chemically modified)	Maxilla	52.4 ± 7.4	53.5 ± 5.3	1.5	0.73
	Mandible	64.2 ± 5.0	64.1 ± 3.5	1.5	–0.06
SLA and TPS[48] ‡	Maxilla	48.8 ± 3.6	53.1 ± 9.5	> 12	0.36
SPI[39] (sandblasted and acid-etched)	Type IV bone	68.9 ± 4.3	69.9 ± 4.3	2	0.51
Photofunctionalized surface (most were complex cases)	ISQi < 40	37.7 ± 2.3	63.0 ± 7.5	AH	4.6
	ISQi 40–49	47.6 ± 1.8	73.8 ± 8.6	AH	8.7
	ISQi 50–59	56.1 ± 2.7	66.8 ± 8.7	AH	2.6
	ISQi 60–64	62.8 ± 1.5	74.0 ± 7.2	AH	2.0

*Values read from the graph.
†Data provided only for differences in ISQ between placement and 3 m follow-up.
‡ISQ data obtained from different patient groups: initial from unloaded patients and secondary from patients loaded > 12 mo.
§Most data obtained at loading, while some obtained at pre-scheduled follow-up time points.
AH: actual healing time before loading; ISQi: initial ISQ at implant placement; NA: not applicable.

75% among different implants.[54,56,57] These indicate that the atomic percentage of carbon is greater than that of titanium in most titanium implants. The C/Ti ratio, which was 109% before photofunctionalization in the present study, was consistent with the literature. Because of carbon removal by photofunctionalization, the implants in the present study may have regained the highest level of innate osteoconductivity, which led to minimal interimplant variation in osseointegration capability.

The known mechanisms underlying the biological effects of photofunctionalization include not only an increased hydrophilicity but also reduced carbon and optimized electrostatic status.[2,3,58] The role of the surface hydrophilicity of biomaterials in determining their bioactivity is contentious.[59] It is not a universal principle that the more hydrophilic the surface, the more biocompatible the material. For instance, under a certain condition, a fewer number of cells attached to hydrophilic titanium surfaces than on hydrophobic

titanium surfaces.[60] A polymer surface with improved hydrophilicity reduces fibroblast proliferation.[61] More hydrophobic polymer scaffold materials are effective in promoting bone regeneration.[62] Although the conversion from hydrophobicity to hydrophilicity is a concomitant phenomenon during UV photofunctionalization, there is not sufficient evidence to support the cause-result relationship between the degree of hydrophilicity and osseointegration capability. In fact, the contact angle of water did not correlate with the rate of osteoblast attachment, although there seems to be a positive effect of higher hydrophilicity on its cell attractiveness.[1,12] Instead, as mentioned above, a substantially reduced amount of surface carbon after photofunctionalization may have contributed more to the present clinical outcome.[1]

A recent study uncovered the importance of surface electric charge to determine the degree of osteoconductivity of titanium.[8,10] Because biological cells are electronegatively charged, if titanium surfaces are electronegative, they repel each other. These studies suggested that the electrostatic property of titanium is important enough to supersede the positive effect of hydrophilicity.[8,10] Unfortunately, sufficiently aged titanium surfaces are known to be negatively charged.[2,3,8,10,63–65] Photofunctionalized titanium surfaces are demonstrated to attract more cells because of their electropositive conversion.[8,10] There are commercially available hydrophilic dental implants, which are stored in a specific solution.[66,67] Recently, the necessity of careful interpretation of the clinical advantage of these surfaces has been pointed out.[59] Little information is available regarding their physicochemical properties, including carbon percentage, electrostatic status, and their time-related changes, which make the interpretation of these surfaces difficult. The definitive difference between photofunctionalized implants and those commercial products is that photofunctionalized implants are dry and converted to chemically clean and genuine titanium surfaces, not wet or accompanied with ions or molecules prior to implantation.

The interpretation of the present results should be limited to the retrospective study design and the follow-up period of up to 2.5 years. Implant stability was evaluated only in photofunctionalized implants. However, the authors believe the reported successful outcomes based on thorough comparison with the fully-searched literature warrant further clinical studies, such as a randomized clinical trial, to establish photofunctionalization as an effective measure to advance implant dentistry in multiple directions. Another advantage of photofunctionalization is that it was proven effective on all surface topographies of Ti-based materials examined,[7,68–70] implying versatile applicability to a wide range of dental implants. In other words, the technology does not provoke a competition among different implant products, but rather has potential to increase the inherent biological capability of a given product. Finally, no surgical complications were observed in relation to photofunctionalization, and surprisingly, the percentage of surgical complications was lower with the use of photofunctionalization, suggesting the practicality and safety of this technology.

CONCLUSIONS

Within the limits of this study, which mainly included implant placement in complex cases, the use of photofunctionalization resulted in a high success rate of 97.6%, even with a substantially decreased healing time of 3.2 months before loading as compared with 6.5 months for untreated implants. The ISQ increase per month for photofunctionalized implants ranged from 2.0 to 8.7 depending on their initial ISQ values, and it was considerably higher than that reported in the literature, which ranged from –1.8 to 2.8. The use of photofunctionalization resulted in the more frequent use of implants in 10 mm or shorter and a decrease in average implant diameter. In conclusion, despite more frequent use of shorter and smaller diameter implants, the use of photofunctionalization allowed for a faster loading protocol without compromising the success rate. The outcome was associated with the increased rate of implant stability development for photofunctionalized implants. The results suggest that photofunctionalization may provide a novel and practical avenue to further advance implant therapy.

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