ISSN 0973-2063 (online) 0973-8894 (print)
Bioinformation 22(10): 7438-7441 (2026)
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BIOINFORMATION
Discovery at the interface of physical and biological sciences
BIOMEDICAL INFORMATICS
www.bioinformation.net
Volume 22(10)
Research Article

Received October 1, 2026; Revised October 31, 2026; Accepted October 31, 2026, Published October 31, 2026
DOI: 10.6026/973206300227438

SJIF 2026 (Scientific Journal Impact Factor for 2026) = 8.478
2022 Impact Factor (2023 Clarivate Inc. release) is 1.9

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Citation: Midha *et al.* Bioinformation 22(10): 7438-7441 (2026)

The role of hydrophilic implant surfaces in accelerating early osseointegration: A prospective analysis

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https://www.skdentalcare.in/

ISSN 0973-2063 (online) 0973-8894 (print)
Bioinformation 22(10): 7438-7441 (2026)
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Abstract:
Osseointegration depends on early bone–implant interactions, which may be influenced by surface wettability. This prospective study compared 62 hydrophilic and hydrophobic implants in 48 healthy adults using resonance frequency analysis at placement and 2, 4 and 8 weeks. Hydrophilic implants showed significantly higher stability at 2 and 4 weeks, with comparable values by week 8. At 8 weeks, marginal bone loss was lower with hydrophilic surfaces (0.41 ± 0.19 mm versus 0.58 ± 0.24 mm; p = 0.004), with 100% implant survival. Thus, hydrophilic surfaces may enhance early implant stability and reduce marginal bone loss, although longer follow-up is needed.

Keywords: Dental implant (DI), hydrophilic surface, implant stability quotient, marginal bone loss (MBL), osseointegration, resonance frequency analysis

Background:
Dental implants have become a predictable and widely adopted modality for the rehabilitation of partial and complete edentulism and their long-term success is contingent upon the establishment and maintenance of osseointegration **[1].** Osseointegration describes the direct anchorage of an implant through the formation of bone tissue around it without intervening fibrous tissue and is conventionally divided into primary stability, derived from mechanical engagement with host bone at placement and secondary stability, derived from biological bone formation and remodelling at the implant surface **[2].** The transition between these two phases is characterised by a transient reduction in total implant stability, frequently described as the stability dip, which represents the period of greatest susceptibility to micromotion-induced fibrous encapsulation and early failure **[3].** The physicochemical characteristics of the implant surface critically govern the cascade of events at the bone–implant interface, beginning with the adsorption of water and plasma proteins within seconds of placement and progressing through platelet activation, fibrin scaffold formation, osteogenic cell recruitment and contact osteogenesis **[4].** Micro-roughened surfaces produced by sandblasting and acid etching enhance osteoblast attachment relative to machined surfaces; however, such surfaces are typically hydrophobic owing to the adsorption of atmospheric hydrocarbons and carbonate contaminants during storage **[5].** Chemically modified surfaces produced and stored under conditions that preserve a high surface free energy exhibit superhydrophilic behaviour, with low water contact angles that favour rapid and complete wetting of the surface by blood **[6].** This enhanced wettability has been associated in preclinical models with increased early protein adsorption, greater osteogenic gene expression and accelerated bone-to-implant contact during the initial weeks of healing **[7].** Despite a substantial body of laboratory and animal evidence, prospective clinical data quantifying the magnitude and timing of any early advantage in human patients remain comparatively limited **[8].** Therefore, it is of interest to report whether hydrophilic surface modification attenuates the physiological stability dip and thereby supports earlier functional loading.

Materials and Methods:
This prospective comparative analysis was conducted at the Department of Dentistry, All India Institute of Medical Sciences, Kalyani, India. Systemically healthy adults requiring single or multiple implant-supported rehabilitation in healed posterior sites were recruited consecutively from the outpatient clinic and followed longitudinally over an 8-week early healing period, with stability assessments at placement, 2, 4 and 8 weeks. Ethical approval was obtained from the Institutional Ethics Committee of AIIMS Kalyani (IEC/AIIMS/Kalyani/certificate/2025/024) and written informed consent was obtained from all participants. The manuscript was prepared in accordance with the STROBE guidelines for reporting observational studies. The sample size was determined a priori to provide 80% statistical power to detect a clinically meaningful difference of 4 ISQ units between surface groups at a two-tailed alpha of 0.05, assuming a standard deviation of 5 units, yielding a minimum of 26 implants per group and accommodating an anticipated dropout of 10–15%. Inclusion criteria comprised age 18-65 years, adequate bone volume permitting placement of an implant of at least 3.5 mm diameter and 8 mm length and willingness to comply with follow-up. Exclusion criteria included uncontrolled diabetes mellitus, current tobacco use, pregnancy or lactation, bisphosphonate or corticosteroid therapy, untreated periodontal disease and any need for simultaneous bone augmentation. A total of 48 participants receiving 62 implants were enrolled and completed all follow-up assessments**.** Implants of identical macro-geometry and dimensions were allocated by surface type into a chemically modified hydrophilic group and a conventional hydrophobic sandblasted, large-grit, acid-etched group. All implants were placed by experienced surgeons using a standardised two-stage protocol with copious saline irrigation, a final drill diameter consistent across groups and a uniform

insertion torque target. Implants achieving an insertion torque of 25–45 Ncm were included to standardise primary stability at baseline. Implant stability was quantified non-invasively by resonance frequency analysis using a calibrated device, with measurements expressed as the implant stability quotient (ISQ) on a scale of 1 to 100. Two orthogonal readings were obtained per implant at each time point by a single blinded examiner and averaged. Peri-implant crestal bone level was assessed on standardised periapical radiographs obtained with a paralleling technique and a customised positioning jig at placement and at 8 weeks; marginal bone loss was calculated as the change in the linear distance from the implant shoulder to the first bone-to-implant contact, measured mesially and distally by two blinded calibrated evaluators with discrepancies resolved by consensus. Statistical analysis was performed using STATA version 19 (StataCorp LLC, College Station, TX, USA). Normality was assessed using the Shapiro–Wilk test. Continuous variables were expressed as mean ± standard deviation and categorical variables as frequencies and percentages. Between-group differences at each time point were assessed using the independent samples t-test or Mann–Whitney U test as appropriate. Temporal changes in ISQ across the four time points were evaluated using repeated-measures analysis of variance with Bonferroni-adjusted post-hoc comparisons and the group-by-time interaction was examined to determine whether stability trajectories differed by surface type. Marginal bone loss was compared between groups using the independent samples t-test. A two-tailed p-value of < 0.05 was considered statistically significant.

Results:

A total of 48 participants receiving 62 implants were enrolled between January 2025 and September 2025 (32 hydrophilic and 30 hydrophobic implants) and all completed the 8-week follow-up. The two groups were comparable at baseline with respect to age, sex, implant dimensions and insertion torque **(Table 1).** Mean ISQ at placement was similar between groups **(Table 2),** reflecting comparable primary stability (71.8 ± 4.2 in the hydrophilic group versus 71.2 ± 4.6 in the hydrophobic group; $p = 0.594$). Repeated-measures analysis demonstrated a significant group-by-time interaction ($F = 18.74$, $p < 0.001$), indicating divergent stability trajectories across the early healing interval **(Table 3).** At 2 weeks the hydrophobic group exhibited the characteristic decline in stability to a nadir of 67.4 ± 4.9, whereas the hydrophilic group maintained a substantially higher value of 72.6 ± 4.0 ($p < 0.001$). The between-group difference remained significant at 4 weeks (75.1 ± 3.8 versus 71.0 ± 4.3; $p < 0.001$), after which the trajectories converged, with no significant difference at 8 weeks (78.9 ± 3.5 versus 77.8 ± 3.9; $p = 0.241$) **(Table 4).** Mean marginal bone loss at 8 weeks was significantly lower in the hydrophilic group than in the hydrophobic group (0.41 ± 0.19 mm versus 0.58 ± 0.24 mm; $p = 0.004$) (**Table 5**). No implant failed during the observation period and early implant survival was 100% in both groups (**Table 6**).

Table 1: Baseline characteristics of the study cohort (62 implants in 48 participants)

Variable	Hydrophilic group (n = 32)	Hydrophobic group (n = 30)
Age (years), mean ± SD	44.6 ± 10.2	45.9 ± 9.8
Female, n (%)	15 (46.9)	14 (46.7)
Implant length (mm)	10.2 ± 1.3	10.0 ± 1.4
Implant diameter (mm)	4.1 ± 0.4	4.0 ± 0.4
Insertion torque (Ncm)	35.4 ± 6.1	34.8 ± 6.5

Table 2: Baseline implant stability comparison between groups

Variable	Hydrophilic (Mean ± SD)	Hydrophobic (Mean ± SD)	p-value
ISQ at placement	71.8 ± 4.2	71.2 ± 4.6	0.594

ISQ: implant stability quotient; independent samples t-test

Table 3: Longitudinal changes in implant stability quotient by surface type

Time point	Hydrophilic ISQ (Mean ± SD)	Hydrophobic ISQ (Mean ± SD)
Placement	71.8 ± 4.2	71.2 ± 4.6
2 weeks	72.6 ± 4.0	67.4 ± 4.9
4 weeks	75.1 ± 3.8	71.0 ± 4.3
8 weeks	78.9 ± 3.5	77.8 ± 3.9
Group × time interaction (F)	18.74	
p-value	<0.001*	

**Statistically significant ($p < 0.05$); repeated-measures ANOVA*

Table 4: Between-group comparison of implant stability at each time point

Time point	Hydrophilic ISQ	Hydrophobic ISQ	p-value
Placement	71.8 ± 4.2	71.2 ± 4.6	0.594
2 weeks	72.6 ± 4.0	67.4 ± 4.9	<0.001*
4 weeks	75.1 ± 3.8	71.0 ± 4.3	<0.001*
8 weeks	78.9 ± 3.5	77.8 ± 3.9	0.241

**Statistically significant ($p < 0.05$); independent samples t-test*

Table 5: Marginal bone loss at 8 weeks

Variable	Hydrophilic (Mean ± SD)	Hydrophobic (Mean ± SD)	p-value
Marginal bone loss (mm)	0.41 ± 0.19	0.58 ± 0.24	0.004*

**Statistically significant ($p < 0.05$); independent samples t-test*

Table 6: Early implant survival over the 8-week observation period

Outcome	Hydrophilic n (%)	Hydrophobic n (%)
Implants surviving at 8 weeks	32/32 (100)	30/30 (100)
Early failures	0 (0)	0 (0)

Discussion:

The principal finding of this prospective analysis was that chemically modified hydrophilic implant surfaces attenuated the early decline in implant stability and achieved significantly higher ISQ values at 2 and 4 weeks than conventional hydrophobic surfaces, despite comparable primary stability at placement. The hydrophobic group displayed the well-recognised stability dip at 2 weeks, whereas the hydrophilic group maintained and then increased stability, with the two trajectories converging by 8 weeks. A significant group-by-time interaction confirmed that the difference reflected divergent biological healing rather than baseline mechanical inequality. These observations are consistent with the proposed mechanism by which surface wettability accelerates the early bone–implant interaction. A high surface free energy promotes immediate and complete wetting by blood, enhancing the adsorption of plasma

proteins and the formation of a stable fibrin scaffold along which osteogenic cells migrate during contact osteogenesis **[9].** Hydrophilic surfaces have been shown in preclinical models to upregulate osteogenic differentiation markers and to increase early bone-to-implant contact during the first weeks after placement **[10].** The maintenance of stability through the period that ordinarily corresponds to the nadir of mechanical anchorage suggests that earlier biological bone formation compensated for the physiological resorptive remodelling of the peri-implant bone, thereby narrowing the window of vulnerability to micromotion **[11].** The convergence of stability values by 8 weeks accords with the understanding that surface chemistry exerts its greatest influence during the earliest phase of healing, after which both surface types ultimately achieve comparable osseointegration in healthy bone **[12].** The clinical relevance of the early advantage therefore lies not in a higher ultimate stability but in the potential to shorten the interval before functional loading, an outcome of considerable practical importance for treatment efficiency and patient experience **[13].** The lower marginal bone loss observed in the hydrophilic group is congruent with the stability findings and may reflect a more favourable early peri-implant bone response and reduced early crestal remodelling **[14].** Although the absolute difference was small, the consistency of the direction of effect across both stability and radiographic outcomes strengthens the biological plausibility of an early advantage conferred by surface modification **[15, 16 and 17]**. The study has several limitations. The 8-week observation period was designed to capture the early healing interval and does not address longer-term marginal bone stability or prosthetic survival, which require extended follow-up. The sample was drawn from a single tertiary academic centre and excluded smokers, patients with uncontrolled diabetes and sites requiring augmentation, thereby limiting generalisability to higher-risk populations in whom the influence of surface wettability may differ. Allocation was not randomised and although baseline characteristics were comparable, residual confounding cannot be excluded. Finally, osseointegration was assessed indirectly by resonance frequency analysis and radiography rather than histomorphometry, which remains the definitive measure of bone-to-implant contact but is not ethically feasible in this clinical context.

Conclusion:
Chemically modified hydrophilic implant surfaces improved early implant stability and reduced marginal bone loss compared with conventional hydrophobic surfaces. These benefits may facilitate earlier functional loading, although stability and survival were comparable by 8 weeks. Larger randomised trials with extended follow-up are needed to validate these findings and establish long-term clinical benefits.

Source of funding:
The Multidisciplinary Research Unit Scheme, Department of Health Research, Government of India provided funding for this study. The funders had no role in study design, data collection or analysis, interpretation of findings or in the decision to publish the results.

Conflict of interest: The authors declare no conflict of interest.

Data availability: The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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