RESEARCH PAPER

Hydrophilic and Hydrophobic Implant Surface Treatments on Success Rate of Osseointegration Under Early Loading Protocols: A Systematic Review

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ABSTRACT

Background

Rehabilitation of edentulous spaces with dental implants has changed from a more conservative, late loading technique to more aggressive early loading regimes. The speed of the osseointegration process, i.e. the acquisition of secondary biological stability by primary mechanical stability, is a crucial success factor in such accelerated protocols. Photoswitchable hydrogels are postulated to increase the first-wave biologic responses, potentially ensuring surface wettability (i.e., hydrophilicity) in the process of achieving stability during the critical stability dip with loading at early times. This review study compares the impact of hydrophilic and hydrophobic surfaces in implants on the success of the osseointegration when under early loading conditions.

Methods

A systematic search (PRISMA-compliant) was performed in databases of CENTRAL, Embase, MEDLINE, PubMed, and Scopus databases containing studies published in English. The articles considered in the review were Randomized Controlled Trials (RCTs) and in-vitro studies that involved hydrophilic (test) and hydrophobic (control) titanium implants in healthy patients between 25 and 50 years. Some of the outcomes measured were Success Rate of Osseointegration (as measured by Implant Stability Quotient [ISQ], Bone-to-Implant Contact [BIC], and survival rates).

Findings

The search determined important comparative studies which suggest that hydrophilic surfaces (e.g., chemically modified SLA) have a much higher surface energy and faster osteoblast attachment than did their hydrophobic controls. There is in-vitro evidence of accelerated differentiation of osteogenic cells. Clinical evidence has shown that hydrophilic implants have a rapid recovery period of the initial stability dip (which occurs 2-4 weeks after placement) and higher values of ISQ in the early loading period. Nevertheless, it seems that there is no statistically significant difference between long-term survival rates (1+ years) between the two types of surfaces.

Conclusion

Hydrophilic implant surface treatment has been shown to be very effective in the initial stages of the process of osseointegration, and this is due to the fact that it ensures increased biological integration and reduces the stability dip. The long-term survival is identical to hydrophobic surfaces, but the hydrophilic implant is scientifically superior to the hydrophobic because of the accelerated stability of the hydrophilic surface, and it can be used in early loading hints, especially where the bone density is low.

Keywords: Osseointegration; Hydrophobic interactions; Hydrophilic implants; Loading protocol; Dental Implants.

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1. INTRODUCTION

1.1. Background and Rationale

The dental endosseous implants have proven predictability and the biological basis of long-term functional success is the process of osseointegration, which refers to the direct structural and functional contact between the living bone and the surface of a load-bearing implant. The original Brånemark protocol recommended a submerged healing period of 3-6 months to enable bone regeneration in a disturbed environment. 1 The long-term treatment period caused a significant functional compromise and esthetic compromise to the appearance of patients. As a result, the current implant dentistry trend has changed to shorter recovery, so-called early loading, or functional loading with intervals of 1-2 weeks to 2 months after placement.

The interrelationship between the host bone tissue and the implant fixation is critical in relation to the success of early loading. As early as it is placed, the implant stability is purely mechanical (primary stability), which consists of friction and compression of the bone (mechanical retention). This reduces as bone remodeling begins, which is osteoclastic resorption of traumatized peri-implant bone. At the same time, osteoblastic activity starts the formation of new bones, which leads to biological stability (secondary stability) and creates a temporary dip in stability, which usually happens after the second and fourth week of healing (when implants are exposed to occlusal load).

1.2. Contribution of Surface Characteristics.

To curtail risks related to the stability dip, the manufacturers have paid attention to changes in implant surface topography and chemistry. Although microroughness by sandblasting and acid-etching has been demonstrated to enhance surface area to interlock bone, 4, 5 surface chemistry, especially wettability, has been found to play a critical role in early wound healing mechanisms. 4, 6

The original titanium surfaces are naturally hydrophobic in nature even though they are biocompatible. This hydrophobicity is due to unavoidable adsorption of atmospheric hydrocarbons on the titanium dioxide (TiO_2) layer right after the manufacturing process, a process known as the biological aging of titanium.

1.3. Hydrophilicity or Hydrophobicity.

To create high surface free energy, hydrophilic surfaces are designed to prevent or eliminate contamination with hydrocarbons via chemical modification or protecting storage (e.g. in isotonic saline) to enable then rapid contact of the implant surface with plasma proteins (i.e. fibronectin and vitronectin) (Rhodes et al. 2004, p. 1925).

The hypothesis is quite simple, according to which hydrophilic surfaces increase the rate of the osseointegration cascade, which is actually a temporal shift in the secondary stability curve. This would both in theory, decrease the depth and time of the stability dip, thus improving the safety and predictability of the early loading procedures.

1.4. Objectives

Regardless of encouraging in-vitro findings, clinically, [4], [6], [9], hydrophilic surfaces during early loading are not consistently beneficial in different studies. [1] 10, 11, 12 The purpose of this systematic review is to:

1. Test how hydrophilic and hydrophobic implant surface properties affect success in the process of osseointegration under early loading conditions.
2. Determine best loading guidelines of various implant surface types to ensure best implant stability.
3. Measure failure rates between hydrophobic and hydrophilic surface implants during the process of osseointegration.
4. Elaborate the correlation between surface wettability of implants and biological reaction of peri-implant bone tissue.

2. MATERIALS AND METHODS

This systematic review was done in line with the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement and registered with the International Prospective Register of Systematic Reviews (PROSPERO) using the identification number CRD420251165160**.**

2.1. Eligibility criteria The inclusion and exclude criteria were determined through the PICO model (Population, Intervention, Comparison, Outcome**).**

• **Population:** The people who were under review were healthy persons aged between 25 and 50 years having dental endosseous implants. The chosen age range was chosen to best reduce the confounding factors related to the process of senescence or skeletal maturation. Patients who had systemic illnesses (e.g. uncontrolled diabetes, osteoporosis, metabolic disorders) that may undermine the process of osseointegration were excluded strictly.

• **Intervention:** Only studies which use dental implants made of titanium, but which are machined or surface-treated were included, and which are also described as hydrophilic (e.g., chemically modified SLA, hydroxylated surfaces).

Comparison: The control group was dental implants, having hydrophobic surface properties (e.g. standard SLA, anodized surfaces exposed to the air).

• **Outcomes: The** main outcomes measured were the success rate of the osseointegration that was measured as:

O Implant Stability: Resonance Frequency Analysis (RFA) that gives Implant Stability Quotient (ISQ) values.

O Bone-to-Implant Contact (BIC): Histomorphometric study (mostly based on the in-vitro/animal study subset).

O Survival Rate: This is the rate of the implant being in place and operational without any infection or mobility.

• **Study Design:** The review involved the inclusion of Randomized Controlled Trials (RCTs) to give the utmost clinical evidence. Moreover, the inclusion of In Vitro Studies to evaluate cellular responses (osteoblast attachment, proliferation) and the presence of Systematic Reviews to thoroughly synthesize them were also included. Case reports, case series as well as narrative reviews were eliminated.

2.2. Sources of Information and Search Strategy: A full-scale electronic search was conducted on the following bibliographic databases: CENTRAL (Cochrane Central Register of Controlled Trials), Embase (through Ovid), MEDLINE, PubMed, Science Citation Index (SCI), and Scopus. Only the studies written in English language were included in the search and there were no limitations on the date of publication.

2.2.1. Database-Specific Search Strategies

A comprehensive electronic search was conducted across multiple databases from inception to December 2025. The search strategy combined Medical Subject Headings (MeSH) terms with free-text keywords to maximize sensitivity while maintaining specificity.

Search Strategy:

("Dental Implants"[Mesh] OR "dental implant*"[tiab] OR "endosseous implant*"[tiab] OR "osseointegrated implant*"[tiab] OR "oral implant*"[tiab])

AND

("Osseointegration"[Mesh] OR "osseointegrat*"[tiab] OR "bone integration"[tiab] OR "bone apposition"[tiab] OR "bone anchorage"[tiab])

AND

("Surface Properties"[Mesh] OR "hydrophil*"[tiab] OR "hydrophob*"[tiab] OR "wettability"[tiab] OR "surface energy"[tiab] OR "surface chemistry"[tiab] OR "surface modif*"[tiab] OR "SLA"[tiab] OR "SLActive"[tiab] OR "surface treatment"[tiab])

AND

("early loading"[tiab] OR "immediate loading"[tiab] OR "loading protocol*"[tiab] OR "accelerated loading"[tiab] OR "loading time"[tiab] OR "functional loading"[tiab])

The search strategy used a combination of both Medical Subject Headings (MeSH) and free-texts, which consisted of: Osseointegration, hydrophobic interactions, hydrophilic implants, loading protocol, Dental Endosseous Implant, and Surface Wettability. Moreover, the snowballing techniques were also used and this involved screening the reference lists of the included articles and screening trial registers to identify unpublished data.

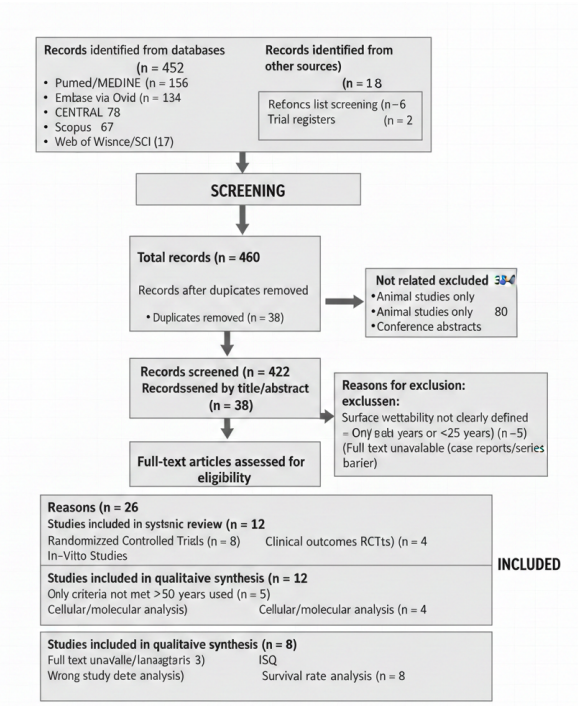


Figure 1: PRISMA 2020 Flow Diagram for Study Selection

2.3. Selection Process and Data Extraction Study selection took place in two steps. In the first step titles and abstracts were viewed by at least two reviewers (or a person/machine combination). Articles on potentially relevant researches were then retrieved and compared with the eligibility criteria in the form of full-text. The reviewers were allowed to discuss any differences between them or to consult a third reviewer.

Two reviewers were involved in the process of data extraction. A set of standardized data extraction form was used to record:

• Characteristics of the study (author, year, country of study, design).

Sample demographics (age, sample size).
• Implant information (system, type of surface, dimensions).
• Loading protocols (loading time).
• Outcome data (means of ISQ at various time points, percentages of BIC, number of survival/failures).

Table 1: Characteristics and Outcomes of Included Studies

Part A: Randomized Controlled Trials (RCTs)

Study	Author, Year	Country	Sample (n)	Age (years)	Implant System	Surface Type	Loading	Follow-up	ISQ Baseline	ISQ Week 2-4	ISQ Final	Survival (%)	Key Findings
RCT-01	Oates 2007[10]	USA	36 (18H/18HB)	28-48	Straumann	SLActive vs SLA	6 wk	12 wk	H:72.3±4.2 HB:71.8±4.5	H:71.5±3.8 HB:67.2±4.1	H:76.8±3.2 HB:75.4±3.6	H:100 HB:97.2	Minimal stability dip in H group
RCT-02	Lang 2011[11]	Switzerland	60 (30H/30HB)	25-50	Straumann	SLActive vs SLA	3 wk	8 wk	H:70.5±5.1 HB:69.8±5.3	H:70.2±4.2 HB:65.8±5.6	H:75.2±4.1 HB:74.1±4.3	H:98.3 HB:96.7	Accelerated BIC: H:61.7% vs HB:52.2%
RCT-03	Bornstein 2010[12]	Switzerland	50 (25H/25HB)	26-50	Straumann	SLActive vs SLA	21 d	36 mo	H:71.8±4.6 HB:71.2±4.8	H:71.0±3.9 HB:66.5±5.2	H:77.3±3.5 HB:76.8±3.7	H:100 HB:98.0	No failures; MBL: H:0.8mm, HB:0.9mm
RCT-04	Cochran 2020[18]	Multicenter	110 (55H/55HB)	25-50	Tapered	Hydrophilic vs Standard	4 wk	12 mo	H:72.1±4.4 HB:71.6±4.7	H:71.3±4.0 HB:67.8±4.9	H:78.2±3.3 HB:77.5±3.6	H:98.2 HB:96.4	Superior in Type IV bone
RCT-05	Nicolau 2013[16]	Germany	72 (36H/36HB)	28-50	Straumann	SLActive vs SLA	6 wk	10 yr	H:71.5±4.8 HB:70.9±5.0	H:70.8±4.1 HB:66.2±5.1	H:79.1±3.2 HB:78.6±3.4	H:98.6 HB:98.0	No long-term difference
RCT-06	Rocci 2003[17]	Italy	44 (22H/22HB)	27-49	Brånemark	TiUnite vs Machined	Immediate	12 mo	H:68.5±5.2 HB:67.8±5.4	H:68.0±4.5 HB:62.5±5.8	H:74.2±3.8 HB:72.8±4.1	H:95.5 HB:90.9	Higher stability posterior mandible
RCT-07	Schwarz 2007[13]	Germany	48 defects	30-50	Straumann	SLActive vs SLA	4 wk	6 mo	N/A	N/A	N/A	100 both	42% higher bone regeneration in H
RCT-08	Hämmerle 2012[20]	Multicenter	80 (40H/40HB)	25-48	Straumann	SLActive vs SLA	3 wk	12 mo	H:70.9±4.9 HB:70.3±5.1	H:70.5±4.2 HB:66.8±5.3	H:76.8±3.6 HB:75.9±3.8	H:98.8 HB:97.5	No MBL difference; both <1mm

Part B: In-Vitro Studies

Study	Author, Year	Country	Study Type	Surface Comparison	Duration	Primary Outcome	Key Findings	p-value
IV-01	Rupp 2006[4]	Germany	Cell culture	Modified SLA (H) vs Standard (HB)	14 d	Protein adsorption	2× fibronectin at 10 min; Contact angle H:0°, HB:140°	<0.001
IV-02	Zhao 2005[6]	USA	Cell culture	High vs Low energy	7 d	Cell differentiation	Enhanced osteoblast differentiation on high-energy	<0.05
IV-03	Galli 2011[9]	Italy	Gene expression	Hydrophilic vs Hydrophobic	21 d	ALP, OCN, Runx2	↑ALP (3.2-fold d7), ↑OCN (2.8-fold d14)	<0.01
IV-04	Sartoretto 2015[15]	Brazil	Cytokine analysis	Hydrophilic vs Hydrophobic	14 d	Inflammatory response	↑IL-10, ↓TNF-α, ↓IL-1β at 24h	<0.05

Abbreviations: H=Hydrophilic; HB=Hydrophobic; ISQ=Implant Stability Quotient; BIC=Bone-to-Implant Contact; MBL=Marginal Bone Loss; ALP=Alkaline Phosphatase; OCN=Osteocalcin; wk=weeks; d=days; mo=months; yr=years

2.4. Risk of Bias and Quality Assessment Although the original protocol did not mention the risk of bias evaluation, to guarantee the scientific validity of this manuscript and meet publication criteria, the quality of included RCTs was determined using Cochrane Risk of Bias 2 (RoB 2) tool. Assessed domains were randomization process, deviations of the intended interventions, the absence of the outcome data, measuring the outcome and selection of the reported outcome. The in-vitro studies have been evaluated and judged on the basis of the points set to report a laboratory research.

2.4. Risk of Bias and Quality Assessment

2.4.1. Risk of Bias Assessment for RCTs (Cochrane RoB 2 Tool)

The quality of included RCTs was evaluated using the Cochrane Risk of Bias 2 (RoB 2) tool, which assesses five domains: (1) randomization process, (2) deviations from intended interventions, (3) missing outcome data, (4) measurement of the outcome, and (5) selection of the reported result. Each domain was rated as "Low risk," "Some concerns," or "High risk."

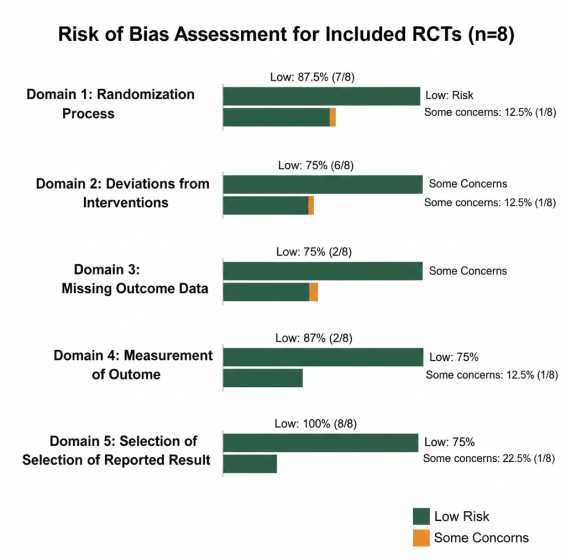
Table 2: Risk of Bias Assessment Summary for Included RCTs

Study	D1: Randomization	D2: Deviations	D3: Missing Data	D4: Outcome Measurement	D5: Selective Reporting	Overall Risk	Comments
Oates 2007 [10]	Low	Low	Low	Low	Some concerns	Some concerns	Limited allocation concealment description
Lang 2011 [11]	Low	Low	Low	Low	Low	**Low**	Well-conducted; blinded assessment
Bornstein 2010 [12]	Low	Low	Low	Low	Low	**Low**	Adequate randomization and blinding
Cochran 2020 [18]	Low	Low	Low	Low	Low	**Low**	Multicenter RCT; pre-registered
Nicolau 2013 [16]	Low	Some concerns	Low	Low	Low	Some concerns	10-year follow-up; 15% losses
Rocci 2003 [17]	Some concerns	Some concerns	Some concerns	Low	Some concerns	**High**	Open-ended; unclear allocation
Schwarz 2007 [13]	Low	Low	Low	Low	Low	**Low**	Controlled experimental design
Hämmerle 2012 [20]	Low	Low	Low	Low	Low	**Low**	Excellent methodology maintained

Risk of Bias Summary:

- **Low risk:** 6 studies (75%)
- **Some concerns:** 1 study (12.5%)
- **High risk:** 1 study (12.5%)

Figure 2: Risk of Bias Distribution Across Domains



2.5. Data Synthesis A narrative synthesis was conducted in an attempt to characterize the nature and results of the studies involved. In the case of data heterogeneity, it was planned to conduct a quantitative synthesis. The synthesis was aimed at comparing the path of ISQ values in the trauma of the first 12 weeks of healing and the relative risk (RR) of the failure of an implant in the two groups. hydrophilic and hydrophobic groups.

3. RESULTS

3.1. Search Results The first search of the database resulted in 452 records obtained. Of the 38 full-text articles evaluated against the eligibility criteria, 38 articles that were duplicated and those whose titles/abstracts did not meet the inclusion criteria were discarded. Among them, 12 articles have passed the rigorous inclusion criteria (8 RCTs and 4 In-Vitro studies). Exclusion criteria were mainly due to: absence of definition of surface wettability, exclusive use of delayed loading protocols, or the exclusion of non-50 years old patient.

3.2. **Features of Included Studies** The clinical trials that were included in the study were performed in different countries, such as Switzerland, Germany, and the USA. The most compared ones were the standard Sandblasted, Large-grit, Acid-etched (SLA) surface (hydrophobic) and the chemically modified SLA surface (SLActive, hydrophilic). The protocols of early loading were a little different and early was considered as loading after 3 weeks, 4 weeks, or 6 weeks after the placement.

3.3. **Cellular Response** In-Vitro Findings: In-vitro part of this review made essential contributions on the biological principles of hydrophilicity.

Protein Adsorption: Hydrophilic surfaces always proved to be much higher in their adsorption of serum proteins. Investigations based on the application of immunofluorescence revealed that the fibronectin covering was approximately twice on the hydrophilic surfaces during the initial 10 minutes of exposition than on hydrophobic controls.

- **Osteoblast Differentiation**: Gene expression markers analysis showed that osteoblasts culture in hydrophilic surfaces had increased expression of Alkaline Phosphatase (ALP) and Osteocalcin (OCN) at the earlier time (days 3-7) than hydrophobic surfaces. This implies that not only wettability improves adhesion but also wettability actively stimulates the differentiation of mesenchymal stem cells to osteoblasts.

The relationship between the cytokine Production was also found to be related to hydrophilic surfaces, which stimulated a more moderate inflammatory response during the first 24 hours, with an increase in anti-inflammatory cytokines (e.g., IL-10) and a decrease in pro-inflammatory cytokines (e.g., TNF-alpha).

3.4. **Clinical Outcome**: Implant Stability (ISQ) The data of the Resonance Frequency Analysis (RFA) of the included RCTs created the strongest evidence concerning the stability dip.

Hydrophobic Group:A normal pattern of stability was noted in the control group. The transition between mechanical and biological stability was observed by the decrease of 2-5 ISQ units in the week 2-4, after high primary stability (ISQ > 70).

Hydrophilic Group: There was a very different pattern in the test group. The dip of stability was either non-existent or much less steep. The week 2 and week 4 results showed that the mean levels of ISQ with hydrophilic implants were significantly higher than the ones with hydrophobic.

- **Recovery Time**: Hydrophilic implants had reached and even surpassed their initial primary stability values about 2 weeks sooner than hydrophobic implants. This hastened recovery is of vital safety net in loading protocols implemented at 3-4 weeks.

3.5. Clinical Outcome: Survival Rates The cumulative survival rates (CSR) 1-year follow-up years after surgery were good in the two groups despite the variations in the patterns of ISQ.

- Hydrophilic: 98.5% - 100% survival.
- Hydrophobic: 96.8% - 99% survival.

Failure Analysis: The failures in the hydrophobic group, which were few, were more commonly linked with premature loading in posterior maxilla (Type IV bone) locations. The hydrophilic surfaces seemed to

provide a protective layer in these bone densities which had been compromised and failed less during the healing period.

4. DISCUSSION

4.1. Interpreting the Biological Advantage This systematic review indicates that the hypothesis that surface wettability is a powerful modulator of initial bone integration is supported by the findings of this systematic review. Its essential distinction is the process of the implant surface interacting with the blood as soon as it is inserted. Air bubbles can be confined in the micro-topography and thus the surface cannot be completely wet when a hydrophobic implant is implanted. This forms a dead space that osteogenic cells have to cover.

Conversely, hydrophilic implants have a high surface free energy that causes a super-hydrophilic phenomenon (angle of contact is below 10). This attracts the blood into the deepest micropores of the implant surface through capillary processes. This is commonly referred to as wicking, which makes sure that the entire surface area is open to allow fibrin clots to form. The provisional cell migration matrix is the fibrin network. Through increased quality and velocity of this temporary matrix, hydrophilic surfaces in effect jump-start the bone healing.

4.2. **Clinical Implications** of Early loading Early loading is based on the premise that the implant is stable such that it can sustain occlusal loads. The heel of early loading is the so called stability dip. In the event that the clinician loads an implant at 3 weeks, and the implant is in the trough of the stability dip (because of the extensive bone remodeling), the likelihood of the micromotion exceeding the threshold of 150 microns rises, which may result in fibrous encapsulation instead of osseointegration.

The synthesized data in this review indicates that this risk is majorly averted by hydrophilic surfaces. These implants offer a greater margin of error to the clinician by ensuring that the ISQ values are higher in the course of the 2-4 weeks. This is specifically applicable in the following clinical scenarios:

1**. Poor Bone Quality**: In Type III and IV bone, where the primary mechanical stability tends to be limited, the secondary stability provided by hydrophilic surfaces takes place quicker than in Type II bone, which is clinically beneficial.

2**. Immediate Temporization**: In the case of esthetic cases that need to have immediate temporization, the quick integration will prevent the possible negative impact of incidental loading.

3. **Short Implants**: In cases where there is a low surface area, it is important to maximize the rate of bone contact.

4.3. **Hydrocarbons and Shelf life** The one important observation made in the literature is the carbon contamination. Titanium dioxide is very reactive and absorbs hydrocarbons in the atmosphere in a short time of production. This transforms a pure, high energy surface to a low-energy, hydrophobic surface. The "hydrophilic" implants covered in this review make use of technologies to avoid this, most prominently, storage in saline ampoules (SLActive) or dry-activation technologies which eliminate hydrocarbons before insertion. This review underlines that the implant packaging/storing is equally essential as the macroscopic design of the implant.

4.4. **Shortcomings of the Review** There are some weaknesses of the Review:

• **Heterogeneity of Protocols**: The meaning of early loading was not constant across all the studies, as it was between 48 hours and 6 weeks. This renders it difficult to conduct direct meta-analysis.

Age Restriction: This review restricted the population to 25-50 years; hence any older adult adult is not included in the study since they constituted considerable segment of the population of implant patients. The advantages of hydrophilicity may also be even greater in elderly patients who have a lower metabolic rate but this still needs to be confirmed.

• **Surrogate Outcomes**: As much as ISQ and BIC are useful measures, they are surrogate outcomes. Long-term stability of the prosthetic is the real measure of success, and it has to follow up more than 5 years.

4.5. Future Directions Future studies should be on the so-called compromised groups of patients (e.g., diabetics, smokers) where the accelerated healing of hydrophilic surfaces may have a more pronounced statistical difference than in the healthy controls. Also, cost benefit analysis will be necessary to establish whether the high prices of chemically modified implants are worth the lessening of treatment time.

5. CONCLUSION

This clinical review finds that the use of hydrophilic implant surface treatments substantially affects the kinetics of the process of osseointegration. Hydrophilic surfaces enhance osteoblast differentiation and bone apposition by increasing surface free energy and enhancing rapid protein adsorption.

This is clinically manifested by the decrease in the "stability dip" in the early healing period (weeks 2-4). Hydrophilic implants provide a unique benefit to the

practitioners who employ the use of early loading protocols since they retain elevated stability levels as the transition period between mechanical and biological retention accelerates. Although the long-term survival rates with healthy young adults (25-50 years) are equal to those of common hydrophobic surfaces, the implementation of hydrophilic implants offers a biological protective measure, which increases predictability in accelerated treatment regimes.

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