Microscopic Analysis of Surface Microtopographic Characteristics of Different Dental Implants

Abstract

Objective
To compare the microtopographic surface characteristics of dental implants with different surface treatments using optical and scanning electron microscopy.

Materials and Methods
Five implant groups (n = 5) were analyzed: Group 1 – NeoKings NK3, Group 2 – SIN Epikut, Group 3 – B&W SG, Group 4 – Straumann BLT, and Group 5 – Neodent GM Helix. Surface morphology was examined under a scanning electron microscope (SEM). Pore diameter and number were quantified using Image Pro-Plus software, while arithmetic surface roughness (Ra) was measured with a confocal laser scanning microscope. Data were statistically analyzed using the Kruskal–Wallis and two-tailed tests, with a significance level of $p < 0.05$ (IBM-SPSS Statistics v.20).

Results
Mean pore diameters (μm) were: Group 5 (1.64 ± 1.40), Group 3 (1.51 ± 1.04), Group 1 (1.32 ± 0.64), Group 2 (1.13 ± 0.64), and Group 4 (1.04 ± 0.87). Statistically significant differences were found among the groups ($p < 0.05$). Pore density (pores/mm^2) was: Group 4 (278,280 ± 45,814), Group 5 (159,129 ± 20,270), Group 2 (76,399 ± 13,405), Group 1 (55,330 ± 9,855), and Group 3 (54,271 ± 14,360). Significant differences were also observed between groups ($p < 0.05$). Mean arithmetic roughness (Ra, μm): Group 5 (1.32 ± 0.25), Group 4 (0.91 ± 0.13), Group 3 (0.87 ± 0.14), Group 1 (0.81 ± 0.08), and Group 2 (0.69 ± 0.09).

Conclusions
Straumann implants exhibited the smallest pore diameters and the highest pore density, suggesting a greater active surface area. Neodent implants presented the highest roughness values. These microstructural variations are clinically relevant, as they directly influence cell adhesion, osteoblastic migration, and ultimately the osseointegration process. Such topographic parameters should therefore be carefully considered when selecting dental implants.

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Authors

Julieta Duer[1]
María Constanza Ibañez[2]
Mario Sezin[2]
Juan Carlos Ibañez[3*]

1
Graduate School, Catholic University of Córdoba, Córdoba, Argentina

2
Professor of the Career of Specialization in Oral Implantology, Graduate School, Catholic University of Córdoba, Córdoba, Argentina

3
Director of the Career of Specialization in Oral Implantology, Graduate School, Catholic University of Córdoba, Córdoba, Argentina

* Corresponding Author

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INTRODUCTION

To enhance the long-term success and survival rates of dental implants, research has focused on surface modifications, particularly surface topography (1), which plays a critical role in early osseointegration between the implant and adjacent bone tissue (2,3). Variations in surface parameters—such as the biomaterial–tissue interface and cellular behavior—can significantly influence the speed and strength of osseointegration. (4)

Surface characteristics, including topography, roughness, wettability (contact angle), and coating composition, are key determinants that mediate biological processes during osseointegration by facilitating direct interactions with host osteoblasts during bone formation. (5,6,7) Rougher surfaces are known to stimulate osteoblastic adhesion, differentiation, and proliferation, as well as enhance mineralization.

Implant surfaces may be machined or roughened, with topographical features classified according to three scales: macro-, micro-, and nano-topography. Macrotopography (10 µm–mm scale) contributes to primary implant stability, while microtopography (1–10 µm scale) enhances bone–implant contact and adhesion. (8) Nanotopography (1–100 nm) influences protein adsorption and cellular adhesion (2,9).

Surface modifications are achieved during manufacturing or post-processing stages to promote optimal osseointegration (10,11). Commonly used treatments include titanium plasma spraying, hydroxyapatite coating, sandblasting, acid etching, and the incorporation of bioactive agents. Techniques such as resorbable blasting media (RBM), sandblasted large-grit acid-etched (SLA) treatments, chemical vapor deposition (CVD), plasma spraying, and plasma electrolytic oxidation (PEO) can significantly strengthen bone–implant bonding (12, 13, 14).

Surface characteristics depend on several factors, including grit size, acid concentration, temperature, and etching duration (15). The resulting roughness affects osteogenic and inflammatory cell responses, influencing healing rate and overall clinical success by improving bone–implant contact (BIC) (16). Surface roughness, expressed as the arithmetic mean roughness (Ra), represents the average height difference between the peaks and valleys of the surface (17).

Structures such as micro-pores—comparable in size to cells—play an essential role in osseointegration. Different levels of roughness yield distinct cellular responses: micro-rough surfaces enhance cell adhesion, while nano-rough surfaces promote cellular differentiation, protein synthesis, and gene expression (18). Nanostructured surfaces also improve antimicrobial properties (19).

An isotropic topography with interconnected macro- and micro-scale irregularities improves osseointegration by increasing mechanical interlocking, surface area, surface energy, protein adsorption, and cellular adhesion during early healing stages (20,21). Micro- and nano-engineered surfaces provide spatial cues that guide cell alignment, proliferation, and differentiation, promoting stronger bone formation (22,23).

Previous research has demonstrated that implant surface morphology, wettability, and roughness are decisive factors influencing cellular responses to biomaterials (24,25). Implants with moderate roughness (Ra = 1–2 µm) exhibit superior bone responses and faster osseointegration (26,27).

Traditional surface modification methods such as sandblasting and acid etching have proven effective but offer limited control over micro/nanotopography. In contrast, advanced surface processing allows precise modification of micro- and nano-scale features, creating biomimetic surfaces that replicate natural bone morphology (28,29). These technological advances hold promise for improving osseointegration and long-term implant performance (30). However, there is still no consensus on the optimal surface geometry for biomedical applications (31). Current findings suggest that the combination of hydrophilic and nanostructured surfaces exerts synergistic effects on cellular behavior (32). Technological characteristics such as porosity, defined micropore size, porosity volume fraction, and particle size present a good biocompatibility profile that facilitates the adhesion, growth, proliferation, and osteogenic differentiation of fibroblasts and osteoblasts (33). The surface physicochemical properties of implants have been shown to influence the cellular response, which in turn affects long-term success (34). In recent years, various surface modification techniques have been developed to optimize the physicochemical and biological properties of implants in contact with bone tissue. This has resulted in the availability of a wide variety of implants with specific and improved characteristics.

The present study therefore aimed to compare the microtopographic surface characteristics of dental implants subjected to different surface treatments using optical and scanning electron microscopy.

MATERIALS AND METHODS

Five implant groups were analyzed according to surface treatments and structural characteristics:

- Group 1: NeoKings NK3 Morse taper connection, 4.20 × 10 mm (Buenos Aires, Argentina; n = 5)
- Group 2: SIN Epikut CM 4.5 × 10 mm (São Paulo, Brazil; n = 5)
- Group 3: B&W SGI (Buenos Aires, Argentina; n = 5)
- Group 4: Straumann SLA RC 4.1 × 10 mm (Waldenburg, Switzerland; n = 5)
- Group 5: Neodent GM Helix 4 × 10 mm (Curitiba, Brazil; n = 5)

Microscopic Analysis

Implants from each group were observed using scanning electron microscopy (SEM) (Carl Zeiss Σigma and Crossbeam 550, EBSD-FE-SEM). All examinations were

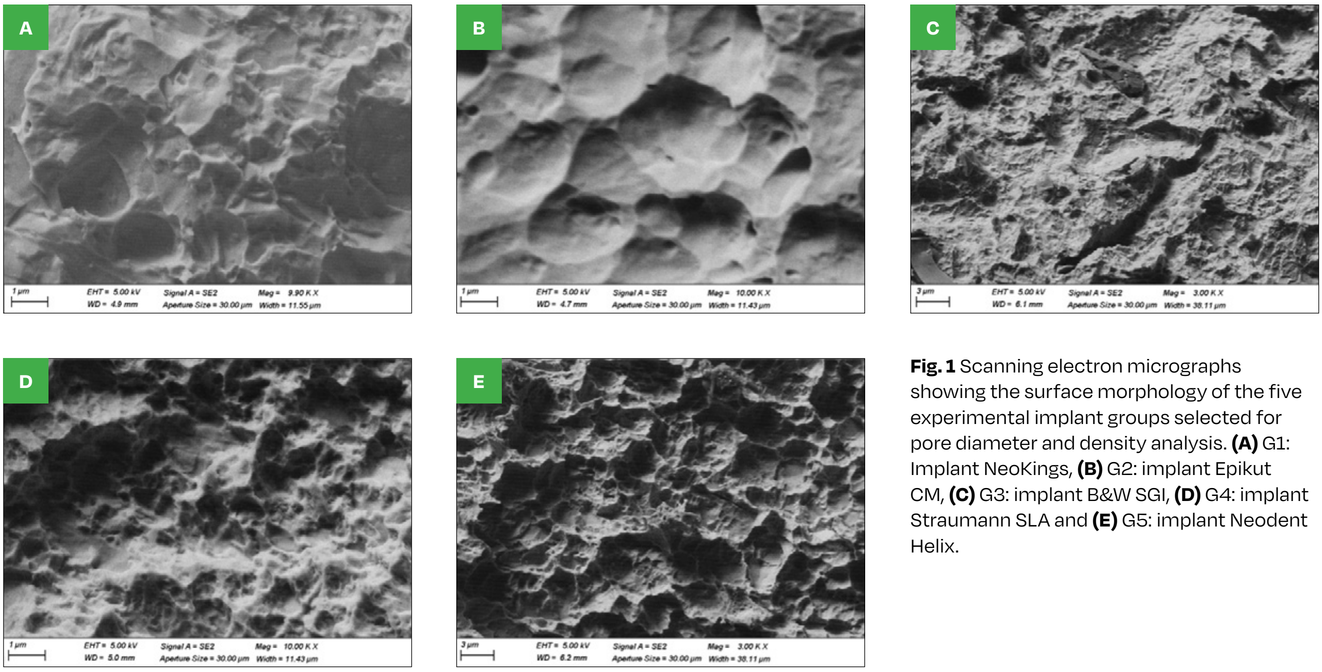

Fig. 1 Scanning electron micrographs showing the surface morphology of the five experimental implant groups selected for pore diameter and density analysis. **(A)** G1: Implant NeoKings, **(B)** G2: implant Epikut CM, **(C)** G3: implant B&W SGI, **(D)** G4: implant Straumann SLA and **(E)** G5: implant Neodent Helix.

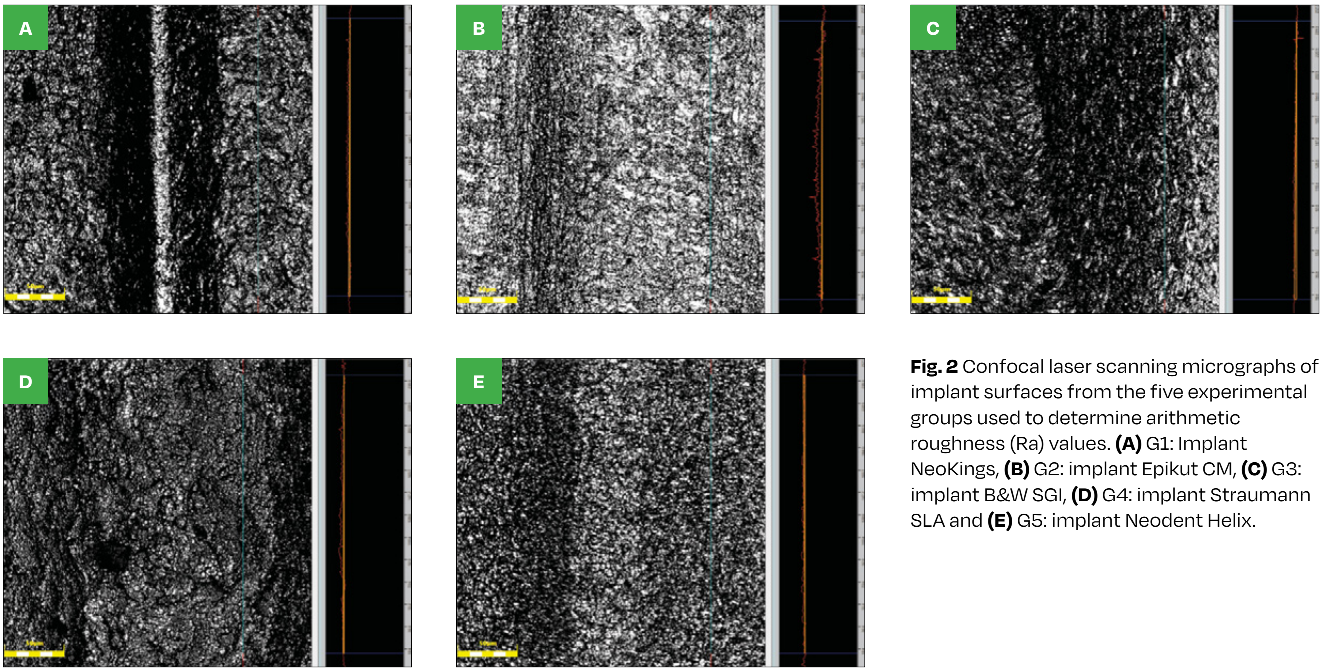

Fig. 2 Confocal laser scanning micrographs of implant surfaces from the five experimental groups used to determine arithmetic roughness (Ra) values. **(A)** G1: Implant NeoKings, **(B)** G2: implant Epikut CM, **(C)** G3: implant B&W SGI, **(D)** G4: implant Straumann SLA and **(E)** G5: implant Neodent Helix.

conducted at the *Laboratorio de Microscopía Electrónica y Análisis de Rayos X (LAMARX, Córdoba, Argentina)*. Surface morphology was analyzed in three regions of each implant: coronal, middle, and apical sections. Samples were mounted on carbon disks and placed in the vacuum chamber of the microscope. Once the vacuum reached approximately 5×10^{-1} mbar, high voltage was activated, and images were captured. Three micrographs were obtained per specimen (Fig. 1).

Pore Measurement

Pore diameter and density (number of pores per mm^2) were quantified using Image Pro-Plus 4.5 software. Each pore was outlined to calculate its corresponding area, average diameter, and count per unit area (mm^2). Pores smaller than 1 µm in diameter and indeterminate structures were excluded from analysis.

Surface Roughness

Arithmetic mean surface roughness (Ra, expressed in µm) was determined using a confocal laser scanning microscope (OLYMPUS Lext 3D) with LEXT-OLS4100 software. Twelve points were mapped on each sample to obtain mean Ra values (Fig. 2).

Statistical Analysis

Data obtained for pore diameter, pore density, and arithmetic surface roughness (Ra) were expressed as measures of central tendency (mean and median) and dispersion (standard deviation, minimum, maximum, and interquartile range, IQR).

Group comparisons were performed using Kruskal–Wallis and two-tailed tests, with a significance level of $p < 0.05$ for all analyses.

Statistical processing was carried out using IBM SPSS Statistics v.20 software.

RESULTS

Pore Diameter

The results are shown in table 1. Statistically significant differences were found among the implant groups (Kruskal–Wallis: $p < 0.05$).

Two homogeneous subsets were identified:

- Subset A, comprising Groups 5, 3, and 1, which presented the largest pore diameters.
- Subset B, consisting of Groups 2 and 4, which exhibited smaller pore sizes.

Pore Density

Significant intergroup differences were also observed for pore density (Kruskal–Wallis: $p < 0.05$). Table 2

Three homogeneous subsets were established:

- Subset A: Group 4 (Straumann), which presented the highest pore density.
- Subset B: Group 5 (Neodent), showing intermediate values.
- Subset C: Groups 2, 1, and 3, which exhibited lower and statistically similar pore counts.

Surface Roughness (Ra)

Arithmetic mean surface roughness (Ra) was used to describe implant surface texture. Statistically significant differences were observed among the groups (Kruskal–Wallis: $p < 0.05$). Results are shown in table 3.

- Group 5 (Neodent) exhibited the highest roughness values, forming Subset A.

Group: Implant	Mean	SD	Median	Min	Max	IQR	Subset
G5: Neodent Helix	1.64	1.40	1.15	0.25	7.36	1.47	A
G3: B&W SGI	1.51	1.04	1.19	0.39	5.90	0.99	A
G1: NeoKings	1.32	0.64	1.16	0.43	4.07	0.93	A
G2: Epikut	1.13	0.72	0.88	0.33	4.37	0.83	B
G4: Straumann	1.04	0.87	0.79	0.20	7.42	0.72	B

Tab. 1 Pore diameter — Mean, standard deviation (SD), median, minimum, maximum, and interquartile range (IQR) by group. Values are expressed in micrometers (µm). Groups with the same letter (subset) do not differ significantly ($p > 0.05$); groups with different letters show significant differences ($p < 0.05$).

Group: Implant	Mean (pores/mm²)	SD	Median	Min	Max	IQR	Subset
G4: Straumann	278,280	45,814	273,642	231,092	334,746	72,304	A
G5: Neodent Helix	159,129	20,270	160,696	134,454	180,672	31,906	B
G2: Epikut	76,399	13,405	73,684	63,291	94,937	17,928	C
G1: NeoKings	55,330	9,855	53,747	46,316	67,511	15,923	C
G3: B&W SGI	54,271	14,360	51,579	40,084	73,840	20,036	C

Tab. 2 Pore density — Mean, standard deviation (SD), median, minimum, maximum, and interquartile range (IQR) by group. Values are expressed as pores per square millimeter (pores/mm²). Groups with the same letter (subset) do not differ significantly ($p > 0.05$); groups with different letters show significant differences ($p < 0.05$).

Group: Implant	Mean (µm)	SD	Median	Min	Max	IQR	Subset
G5: Neodent Helix	1.32	0.25	1.29	0.95	1.74	0.43	A
G4: Straumann	0.91	0.13	0.90	0.76	1.17	0.21	B
G3: B&W SGI	0.87	0.14	0.83	0.70	1.18	0.24	B
G1: NeoKings	0.81	0.08	0.83	0.63	0.96	0.09	B
G2: Epikut	0.69	0.09	0.66	0.58	0.86	0.18	C

Tab. 3 Arithmetic mean roughness (Ra) — Mean, standard deviation (SD), median, minimum, maximum, and interquartile range (IQR) by group. Values are expressed in micrometers (µm). Groups with the same letter (subset) do not differ significantly ($p > 0.05$); groups with different letters show significant differences ($p < 0.05$).

- Groups 4, 3, and 1 displayed intermediate roughness, grouped as Subset B, whereas Group 2 (Epikut) had the lowest roughness values, forming Subset C.

DISCUSSION

The aim of this study was to compare the microscopic surface characteristics of dental implants produced by different surface treatments, focusing on pore size, pore density, and arithmetic surface roughness (Ra). These topographical variables are directly related to the establishment of adequate primary stability during implant insertion and play a decisive role in osseointegration at both mechanical and cellular levels.

The results demonstrated that Straumann implants presented the smallest pore diameters (mean 1.04 µm), while Neodent implants exhibited the largest (mean 1.64 µm). Neodent, B&W, and NeoKings implants showed no statistically significant differences in pore size among them, whereas Epikut and Straumann also shared similar diameters.

Regarding pore density, Straumann implants presented the highest number of pores (278,280 pores/mm^2), followed by Neodent (159,129 pores/mm^2). Epikut, NeoKings, and B&W implants displayed lower and statistically comparable pore densities.

Surface roughness (Ra) measurements revealed that Neodent implants had the highest roughness values (1.32 µm), while Epikut exhibited the lowest (0.69 µm). Straumann, B&W, and NeoKings showed intermediate roughness values, without significant differences among them.

Osseointegration is fundamental to the long-term success of endosseous dental implants. Surface-related factors—such as roughness, topography, energy, and chemical composition—strongly influence this process. The formation of micropores contributes to micro-roughness, which enhances mechanical interlocking and bone-to-implant contact (BIC), thereby improving primary stability and the mechanical anchorage of the implant to mineralized bone (35).

Surface characteristics are developed through various manufacturing methods, such as machining, acid etching, anodization, plasma spraying, grit blasting, or combined techniques, all designed to optimize surface properties, biocompatibility, and bioactivity with bone tissue. (36) Previous studies have shown that well-characterized implant surfaces, with pore diameters between 1 µm and 10 µm, can improve the understanding of how surface morphology influences biological responses (37). Modifications at the nanometric scale have been reported to enhance hydrophilicity, protein adsorption, cell adhesion and migration, mineralization, and osteogenic gene and protein expression (38). In vitro and in vivo studies consistently show superior osseointegration for roughened surfaces compared with smooth or machined ones (26), highlighting the greater relevance of surface morphology over composition in determining biological response (39).

The chemical treatment used on titanium surfaces of different dental implants produces a microtopography with dissimilar and specific characteristics for each implant brand analyzed (40). The results show that porous dental implants with complex structural features exhibit improved mechanical and biological properties and can better promote the growth and integration of bone tissue (41). There is clear relevance regarding the influence of topographic and wettability characteristics at the macromolecular and cellular levels in the endosseous interfaces between implants and biological systems. Obtaining complex multiscale surfaces, including distinctive nanotopographies and wettability properties, remains a technical challenge (42).

An important parameter for the clinical success of dental implants is the formation of direct contact between the implant and the surrounding bone, whose quality is directly influenced by implant surface roughness. The highest arithmetic mean roughness (Ra) values corresponded to Neodent implants (1.32 µm), while the lowest values were observed in Epikut implants (0.69 µm). Straumann, B&W, and NeoKings implants did not differ from one another. It has been reported that surfaces with an average roughness of 1–2 µm yield better outcomes. Reported values for Neodent implants include 0.67 µm of surface roughness (43). Another study reported roughness values between 0.69 and 1.35 µm (37).

Implant surface modifications provide structuring, roughness, and biological activation that promote osteogenic differentiation, and the initial cellular response to the implant material is a key factor for stable, long-term successful integration (44). It has been demonstrated that implants with rough surfaces have better bone apposition and higher BIC compared to smooth surfaces (45). Different ways to classify surface roughness have been proposed: smooth or machined (Sa < 0.5 µm), minimally rough (Sa 0.5–1 µm), moderately rough (Sa 1–2 µm), and rough surfaces (Sa ⩾ 2 µm). These findings have led to increased research on the behavior of hard and soft tissues around titanium and zirconia dental implants. Enhanced bone cell behavior has been associated with increased surface roughness (39).

A review of the most relevant literature on the role of implant surfaces in the success of biological integration concludes that various surface properties—such as chemistry, roughness, and topography—affect biological responses and determine the interaction between the implant, proteins, and cells. Various techniques and materials used to improve implant surface properties were explained and discussed, including physical and chemical functionalization. Subtractive functionalization methods, including laser treatment and the embedding of bioactive or antibacterial nanoparticles, have shown promising results. However, there is substantial heterogeneity among studies regarding surface characterization methods, cell culture conditions, and cell

types, making comparison difficult (15).
Significant advances have been made in the development of new dental implant surfaces. A review of the literature on different commercial and experimental surface modifications of dental implants and their effect on osseointegration has shown optimal results both in immediate loading protocols and in situations with insufficient bone quantity. These loading conditions require advances in implant surface design and form the basis for rehabilitating patients with a high degree of success and predictable survival rates, even under challenging circumstances (46).
Consistently, the success of a dental implant depends on the chemical, physical, mechanical, and topographic characteristics of its surface. The influence of surface topography on osseointegration has translated into shorter healing times from implant placement to restoration (47). In other words, all implant surface treatments aim to achieve a complex microtopography that has a direct and effective impact on short- and long-term osseointegration processes.
A literature review reported a correlation between implant surface roughness and the stability achieved from the moment of insertion and osseointegration up to three months postoperatively, encompassing all existing study models—human, animal, and experimental. The findings of this review indicate that implant surface roughness does not affect primary stability; rather, it is directly involved in secondary stability. This is because surface texture affects the rate of osseointegration, influencing overall implant stability. A correlation has been observed between the degree of surface roughness and the degree of osseointegration achieved, defined as bone–implant contact (48).
Modification of implant surfaces is essential for improving osseointegration, thereby contributing to the long-term success of dental implants. Similarly, it is affirmed that topographic alterations, such as roughness and nanostructuring, enhance mechanical interlocking and cellular adhesion. Currently, chemical modifications—including surface coatings and bioactive treatments—improve biocompatibility and osteoconductive properties. Biological enhancements, such as the incorporation of growth factors and bioactive molecules, also accelerate bone consolidation and integration. By combining these strategies, implant surfaces can be optimized to facilitate faster and more effective osseointegration, ultimately resulting in better clinical outcomes (49).
Despite technological developments in the field of biomaterials, the ideal surface roughness for osseointegration remains a challenge. Technological innovations such as nanoscale surface roughness are needed to accelerate osseointegration; however, the clinical relevance of the relationship between nanoscale roughness in dental implants and osseointegration is still under investigation (50). Nanotechnology applied to create nanostructured implant surfaces is capable of inducing bone cell adhesion, osteoblastic growth and differentiation, and greater bone tissue integration (51).
Understanding the mechanisms of osseointegration, as well as applied knowledge of dental implant surfaces characterized by microroughness and nano roughness, chemical composition, and physical and mechanical parameters, is fundamental for achieving satisfactory clinical outcomes. An isotropic and moderately rough surface has shown better clinical results compared to minimally rough surfaces. However, there is no clinical evidence supporting any particular type of nano roughness pattern (52).
Technological advances have greatly expanded the methods for implant surface modification. Therefore, current nanostructured dental implants represent an evolutionary advancement over conventional microrough implants; however, continued research and development is essential to design optimized surfaces based on fundamental science, thereby driving technological progress in this field (53).
Validating changes in implant surface topography and chemical or physical features through lab and clinical studies is crucial for understanding their impact on repair and long-term osseointegration. It is crucial to highlight the synergistic interrelationship between pore size (µm), pore density (pores/mm^2), and arithmetic roughness (µm) on dental implant surfaces. Precise control of these topographic and morphological characteristics is essential for optimizing osseointegration. Simultaneously, the presence of complex interconnected porosities and high pore density favors bone deposition. A moderate surface roughness (1 µm to 2 µm) has been shown to enhance cell adhesion and proliferation. Therefore, successful implant surface design integrates a well-defined three-dimensional porous microstructure and surface roughness, seeking a balance that promotes long-term stability and the clinical functionality of the implant.

CONCLUSIONS

The morphological analysis of dental implant surfaces revealed significant differences among the brands evaluated in this study. Regarding pore size, a clear grouping was observed: Neodent, B&W, and NeoKings presented similar pore diameters, whereas Epikut and Straumann also exhibited comparable values. Straumann implants stood out for having the smallest pores among all groups. In terms of pore density, Straumann implants showed the highest pore count, while Neodent displayed intermediate values. Epikut, NeoKings, and B&W implants presented similar and lower pore densities compared with Straumann and Neodent. Concerning arithmetic mean surface roughness (Ra), Neodent implants exhibited the highest roughness, followed by Straumann, B&W, and NeoKings, which showed similar intermediate roughness values. Epikut implants consistently presented the lowest Ra values within the set. These findings indicate that each implant manufacturer employs distinct surface modification strategies to achieve specific topographic patterns. Straumann, characterized by smaller and more numerous pores, exhibited a greater active surface area, whereas Neodent demonstrated a higher degree of roughness. The microstructural differences observed in these surfaces are critical, as parameters such as pore diameter, pore density, and arithmetic mean roughness (Ra) directly influence cell adhesion, osteoblastic migration, and ultimately, implant osseointegration. Therefore, these topographic features should be considered key factors in the clinical selection of dental implants, as they may have relevant biological and clinical implications.

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