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Study the Effect of Fibre Laser Irradiation and Dual Acid Etching on Titanium Dental Implant Surface: A Systematic Review

Haneen Abdulsattar [(1) *]
Nihad AlFuraiji [(2)]
Syed Saad B. Qasim [(3)]

[(1,2)] Department of Dental Prosthetic Techniques, in College of Health and Medical Technology, Middle Technical University, Baghdad, Iraq.
[(3)] Department of Bioclinical Sciences in the Faculty of Dentistry of Kuwait University, Kuwait.

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***Corresponding Author:**
Email:
ecc0062@mtu.edu.iq

Postgraduate student at Department of Dental Prosthetic Techniques, College of Health and Medical Technology, Middle Technical University, Baghdad, Iraq.

Abstract

In an effort to increase surface bioactivity, numerous chemical and physical treatments of titanium surface have been made, but there is a rareness of comparable data. The objective of writing this review is to offer a comprehensive and updated source of information about parameters of both fibre laser and dual acid etching surface treatments and their impact on both surface characteristics and biological response of titanium and its alloys. The following keywords were used to discover relevant publications published between 2015 and 2024: "fibre laser," "dual acid etching," "titanium dental implants," "biocompatibility," "surface properties," “corrosion resistance,” and their synonyms. The literature was searched in the PubMed, Google Scholar, Research Gate, and CORE databases. Out of the 220 references that were screened, 36 publications satisfied the requirements for inclusion. Based on the reviewed articles, titanium's surface and biological response were altered by both fibre laser and dual acid etching surface treatments, dependent upon parameters and settings employed. Fibre laser produces a surface that is free of impurities and has a higher of titanium oxide layer while also improving surface topography and roughness in a regulated manner. By eliminating the native titanium oxide layer, increasing surface roughness, enhancing surface reactivity and forming a titanium oxide layer, dual acid etching produces a micro-rough surface that is favorable to bone integration. It has been shown that treatments with fibre laser and dual acid etching alter the surface and biological characteristics of titanium. To optimize the outcomes, protocols with precise parameters must be determined.

Introduction:

Patients who have injuries and oral diseases are typically the ones who experience tooth loss. It causes the alveolar bone to gradually resorb and inhibits the ability to chew(1). Traditionally, people missing teeth have utilized removable prostheses made of acrylic resins to retrieve functional deficiencies and enhance appearance(2). Dental implants, on the other hand, have a number of benefits over removable dentures, including long-term viability and the protection of surrounding teeth(1).

Dental implants are now the most common method of oral restoration, and the most significant area of research interest in this field is implant materials(3). Titanium's mechanical qualities, biocompatibility, resistance to corrosion, and stable oxide surface have made it an effective material for dental implants for more than 50 years(4, 5).

Over dental implants, titanium oxide (TiO_2) creates a thick, firm, and protective layer known as the passive film that is very effective at preventing corrosion. Bone differentiation happens just next to the implanted material in ideal circumstances. The primary prerequisite for the long-term viability of dental implants is osseointegration, which is the direct structural and functional bond between living bone and load-bearing dental implant surfaces(6, 7).

The high corrosion resistance, from one side, is highly desirable for long term chemical stability. On the other hand, Ti and its alloys are bioinert, exhibiting minimum interaction with human tissues. This aspect is a concern regarding implant to bone adhesion, as the cell attachment and proliferation over the metallic surface is minimum in bio-inert materials. Consequently, a compromise between chemical stability and bioactivity shall be attained for the success of the implants(8).

As far as chemical stability (bio-inertness) is concerned, several surface modification processes based on mechanical, physical, chemical, electrochemical, bioactive molecules deposition and laser-based treatments are being used to promote bio-functionalization of Ti alloys(9) and that happened through enhance wettability, cell-implant adhesion and attachment, cell proliferation, osseointegration, and increase surface area which led to quicker healing and a shorter course of therapy. The surface's characteristics determine the dental implant's quality. The osseointegration process is significantly impacted by surface characteristics such as surface topography, charge, energy, and chemical composition(10).

One of these approaches is the laser irradiation, a physical method, which has been developed as an alternative for existing technologies. This approach has gained popularity despite difficulties with the wetting stability of laser-textured surfaces because of its quick processing speed, low technical complexity, simple equipment, and capacity to operate at atmospheric pressure in some areas(11, 12). One type of lasers that well interacts and absorbs by titanium is the fibre laser(13). When it comes to processing fine structures, fiber lasers provide a number of benefits over current technology. These benefits include air-cooling, high-power densities, little heat-affected zones, and ease of laser focus on a tiny point(14). After being exposed to a high intensity laser beam, the surface becomes tridimensional and nanostructured, with improved roughness, wear and corrosion resistance, a contaminants free surface, and an increased titanium oxide layer due to the ablation phenomena. Furthermore, this procedure can be executed in a regulated and repeatable manner(15). Biorespones are mostly dependent on the laser's parameters, which include power, frequency, energy density or fluency (the amount of energy delivered per unit area), and scanning speed(6, 12). Dual acid etching (DAE), a chemical method, is a traditional treatment for the surfaces of dental implants. It involves treating titanium implants with either chemical or acid, either sequentially or in combination. The treatment chemical or acid may optionally be heated before treatment(16, 17). Dual Acid etching mechanism includes removal of the native or contaminated titanium oxide layer which enhancing surface reactivity, then creates roughness with micrometric sized topography, this leading to an increase in surface area, and a new oxide layer can be formed when in contact with moisture in the air(18, 19). It was discovered that a DAE surface enhanced the adhesion of fibrin and osteogenic cells, which in turn promoted bone apposition and improved the osteoconductive capabilities of implants(20).By using selective corrosion, acid etching leaves pits or grooves on the metal surface. Numerous factors, including the types(21) and combinations of acids employed, their concentration, temperature, and treatment duration, influence the precise topography, dimensions, and surface roughness that results(22). This systematic review aims to assess the effectiveness of the parameters of both fibre laser irradiation and dual acid etching treatments in enhancing the bioactivity of titanium dental implant material. By synthesizing existing evidence, we aim to provide insights into the potential benefits of fibre laser irradiation and dual acid etching treatments as an intervention for bio-inertness of titanium biomaterial.

Materials and Methods

Search Methodology

We searched the PubMed, Google Scholar, Research Gate, and CORE databases to find relevant articles published between 2015 and 2024 using the following keywords: fibre laser, AND dual acid etching, AND modification (OR processing, treatment), AND titanium dental implants (OR titanium surface), AND biocompatibility (OR in vitro bioresponse OR cellular activity OR in vivo osseointegration), AND surface properties (OR roughness, topography, wettability, surface chemistry, corrosion resistance). The references of each article were then reviewed to identify other relevant articles. This systematic review assessed whether fibre laser and dual acid etching surface treatments enhanced the surface properties of titanium dental implants. Table 1 outlines the questions that were addressed with reference to participants (P); intervention (I); control (C); outcome (O); and study design (S) (PICOS elements).

Inclusion Criteria

Included articles were titanium dental implants that had undergone dual acid etching or fibre laser treatment. Studies that look at how these treatments affect the surface characteristics and osseointegration of titanium dental implants include clinical, in vivo, and in vitro investigations. Regarding the titanium grade and the parameters of the fibre laser and dual acid etching, no distinction was made. studies that are only available in English. A range of publications from 2015 to 2024 was covered.

Exclusion Criteria

The exclusion of publications written in languages other than English. Excluded from consideration were studies on contaminated implants in which DAE and a fibre laser were used to drive implant surface disinfection. Studies on orthopedic implants, PEEK and zirconia implants, and abutments were also disqualified. Research on surface treatments other than dual acid etching or fibre laser irradiation.

Data Extraction

The information gathered from many situations, including in vitro, in vivo, and clinical investigations describing DAE and fibre laser irradiation surface modifications or treatments of titanium dental implants. The

data was synthesized without statistical analysis because there is no heterogeneity in the parameters, cell types, types of fibre laser and acids, or other factors.

Results

After evaluating the titles and abstracts of 220 papers found in the first search, 85 articles were selected. Thirty-six papers were included in this systematic review after the full texts were retrieved. Eighteen studies examined surface modification or treatment with DAE, and eighteen examined the surface modification utilizing fibre laser. The 36 articles were published in the period from 2015 to 2024. Tables 2 and 3 present an overview of the parameters and outcomes based on the technique that was utilized. Table 2 illustrates the widespread usage of commercial pure titanium as a dental implant material in research (12 studies utilized commercial pure titanium, and 4 studies used Ti6Al4V alloy). The surface pattern or topography produced by the fibre laser treatment was the most important variable (the majority of research focused on the effect of topography on osseointegration), and all studies show a positive result on the enhancement of the surface properties. However, the parameters of the fibre laser used in these studies were not mentioned in detail. Also, the fibre laser surface treatment enhances the bioactivity of titanium dental implant surface, and increases the cell adhesion, differentiation and proliferation. Table 3 illustrates Ti6Al4V alloy and commercially pure titanium grade 4 are widely used in the studies of DAE surface treatment, most of the studies did not mention the parameters of DAE in details, the increase of roughness is in low value in most studies so the topography of surface plays an important role in the bioactivity. A positive effect of DAE surface treatment on cell viability, and improving osseointegration process. However, Del Fabbro et al. revealed inflammatory cells were clearly detected around implant with DAE surface made of titanium alloy.

Discussion

The surface of titanium dental implants modifies by fibre laser irradiation, resulting in a surface that is tridimensional and nanostructured. This modification greatly improves wear and corrosion resistance as well as surface roughness. Notably, the ablation event causes a surface free of contaminants and an increase in the titanium oxide layer(15).

Numerous factors, such as the laser's power, frequency, pulse energy, energy density, and scanning speed, affect how successful fibre laser irradiation is. These characteristics are essential for characterizing the biological reactions of modified surfaces(12). In table 2 almost all presented studies (23-39) have reported changes in surface topography, fibre laser can produce regular, homogenous, and controlled surface topography with a multiscale hierarchical structure composed of micro-features and nano-features (23, 24, 26-39) through its controlled and adjustable parameters including: power, pulse duration, pulse energy, scanning speed, frequency, and also scan number and type (23, 24, 34, 35, 37) and accomplished through a software program which used to convert the surface texture detailed to laser machine instruction files(32).

The most important factor influencing the critical laser intensity is the pulse duration. Increased depth of melting and more precisely formed metallic lotus leaf patterns were achieved by lengthening the pulse duration at constant laser power density. These frozen melted droplets acted as flexible bearings, stimulating activation energy at the first step and maintaining inertia in movement to break the stress shielding effect at the bone-implant interfaces at the second step(23).

Lowering laser penetration depth results by the increasing of laser frequency which cause narrowing of parallel grooves in both width and depth because of the lowered induced energy(35). By increasing the diameter of laser beam resulted in an increase in the number of microcracks because of high temperature gradients and the lack of isothermality in the laser surface oxidation process(27, 29). There has been a noticeable increase in surface roughness (24, 26-32, 34-36, 38), which is beneficial for bone formation(12), adherence(24, 35), proliferation(30), and the life-sustaining activities of cells(34). This is because it increases the contact area between the implant and bone(12). There has been research on the ideal roughness range for the Ra parameter, which is between 1 and 2 μm; very high or very low roughness may inhibit cell growth(29). The interaction between cells and implant surfaces is influenced not only by surface micro-roughness but also by topography, which includes continuous topography with features less than 50µm and the presence of nanostructures. Surface roughness that is significantly greater than 2µm has a positive effect on osteogenesis, as demonstrated by previous research(34).

Fibre laser irradiation can increase surface roughness in low amount, despite the majority of research reporting an increase in high amount, depending on the parameters utilized such as high scanning speed, laser direction, small laser beam diameter and scan number (24, 26, 30-34). In the cases where the grooving distances are less than 50µm and greater than 50µm, respectively, raising the laser frequency has two opposite effects on the average surface roughness: increasing and reducing but it still higher than untreated surface(35).The majority of articles (25, 28, 29, 31, 34, 36, 38) demonstrated a decrease in the contact angle, a notable improvement in the wettability feature, and an increase in the hydrophilicity of the fibre laser-treated surface. However, surface topography can cause an increase in the contact angle and a reduction in wettability by increasing the groove distance(35) and the orientation of grooves(26). These findings highlight the variation in wettability outcomes following fibre laser surface treatment. On the other hand, topography, roughness, and chemical composition can all have an impact on wettability. Hydrophilic behavior is influenced by the high oxygen concentration and rise in titanium oxides that come with laser irradiation. Because air entrapment in surface imperfections raises the contact angle, which improves hydrophilicity, the interaction with the gas phase is particularly crucial(34, 35).This increased wettability promotes the deposition of bone tissue to cause quick osseointegration by enabling a better and more stable clot adherence to the implant's surface(31, 36).The interface between the implant and the bone is also greatly influenced by the chemical composition of the surface(57). Irradiation of surfaces with fibre lasers can encourage the creation of titanium oxides or the incorporation of oxygen on irradiated surface (25, 26, 29, 32-34, 37, 39). This is due to the fact that radiation rapidly melts titanium's surface, allowing ambient oxygen to permeate the molten surface and raise the surface oxygen content(36). The thickness of the oxide layer is increased on the titanium surfaces exposed to laser radiation due to the increased oxygen concentration, resulting in a more uniform and thicker layer than what would normally occur on titanium(58).The number of oxide compounds on the surface increases when the laser energy density of the fibre engraving process is increased(35, 36). The internal structure of the metal remains unchanged, only the surface is impacted by the fibre engraving laser process. On the changed surface, the concentration of Al and V elements nearly disappeared.The metallurgical phenomenon of precipitates-dissolution and their precipitation as the supersaturated- phase or martensite helps explain this(35). The presence of carbon was as a contamination from environment or cleaning process. In addition, the laser treatment promoted the oxidation of Ti, Zr, and Nb on the surface of the TZNT alloy that contributed to the improved corrosion resistance of the alloy(26). The contact between the implant's surface and the surrounding air during the laser ablation process led to the presence of oxides and nitrides (TiN) on the surface(27, 36). This means that some material characteristics, like the oxides and nitrites produced by fibre laser irradiation, can encourage higher surface wettability, enhanced hardness, and resistance to corrosion, encouraging osseointegration(36). A significant improvement in corrosion resistance of Ti surfaces after laser ablation due to the formation of more stable oxide layer as well as formation of refined microstructure and microstructural homogenization (26-29, 39, 40). The Zr, Nb oxides and TiN formation and incorporation within titanium oxide layer also enhance corrosion resistance of laser treated surfaces through act as an effective protective barrier to protect substrate material from deterioration and ion release (26, 27, 29, 36). However, the increase of the laser spot (beam diameter) created an oxide layer which is very fragile, low adhered, and heterogenic to the titanium substrate which led to significantly worse corrosion resistance compared with small spot size(29). Using a fibre laser to modify titanium's surface can lead to the formation of hierarchical multiscale structures where nanostructures cover microstructures. It has been demonstrated that these composite micro-nano-textures can alter the wettability of the surface and alter the behavior of the cells. Furthermore, it is possible to prevent bacterial cell attachment and growth by precisely regulating the size of the formed structures(30).Table 2 illustrates how surface modification by fibre laser, which produces a controlled topography that is preferred for osteocytes, clearly enhances the intended biological response between bone and implant interface of cell adhesion, proliferation, bone growth, osseointegration and increase bone to implant contact (24-28, 30, 34, 35, 37). Table 3 illustrates how DAE uses a combination of strong acids, usually hydrochloric acid (HCl), nitric acid (HNO3), hydrofluoric acid (HF), and sulfuric acid (H2SO4), or weak acid H_2O_2 to treat titanium implant surfaces. By eliminating the contaminated titanium oxide layer, increasing surface roughness, and a new oxide layer can be formed when being contact with ambient air contributes improving osseointegration through a more porous surface structure, this treatment produces a distinctive micro-texture surface that is favorable to bone integration (17-20, 43-46, 48, 50-52, 56).

The results of DAE are dependent on a number of variables, including the type and concentration of the acid, how long the etching process takes, and the temperature at which it is done. These variables may lead to varying degrees of porosity and surface roughness, which may impact implant osseointegration performance. However, because Ti6Al4V alloy is biphasic, as opposed to commercially pure titanium, which only possesses the α phase, the type of Ti material also affects the level of porosity and roughness that results following DAE treatment(22). The Ti6Al4V alloy's β phase, which is thought to be more unique and etch-resistant, has a crystal shape. The surface roughness of Ti6Al4V alloy is higher than that of commercially pure titanium, which can be explained by the discovery that beta crystals have a size range of 0.5-2 microns (19, 22, 41, 44, 47-49, 51, 56). The chemistry of surface revealed the formation of passive and higher stable titanium oxide layer, also using HCl and HF etchants degrade the native oxide film and react with the surface, forming a TiH intermediate layer, where a new oxide layer can be formed when in contact with moisture in the air. The combination of these two layers may be responsible for the improved potential, polarization resistance which suggests improvement of the corrosion resistance (18, 19, 45, 47, 51).

Table 3 displays the micro-rough surfaces produced by DAE to promote biological responses, such as improved cell adhesion, proliferation, and differentiation. These factors are essential for both good implant integration and bone bonding. The unique micro-rough surface that was formed, which is favorable to bone integration, is principally responsible for the improved cell activity (17, 19, 41, 47, 49, 51, 53, 56). On the other hand, implants with a titanium alloy DAE surface clearly showed the presence of inflammatory cells (but not surrounding implants made of commercially pure titanium). These results are hard to interpret, but they might be connected to a specific mix of surface components in a specific ratio that could cause a tissue reaction(48).

The degree of bone-to-implant contact is a crucial sign of implant success. It has been shown that DAE-treated surfaces encourage stronger and faster bone-to-implant contact, which improves the implant's anchoring in the bone. The long-term viability of dental implants depends on this advancement (42, 48, 55).

Despite these benefits, the DAE surface treatment approach has a number of drawbacks, including the use of hazardous chemicals and the retention of utilized acid residues in the pores(12, 37).

As a result, while both DAE and fibre laser irradiation are an effective surface modification method for titanium dental implants, fibre laser irradiation offers more advantages and potential for advancement to satisfy particular clinical needs in dental implantology.

Conclusion

1. Fibre laser irradiation produces regular and controlled roughness and topography (through the parameters that set using a software program), increase wettability, and enhance surface chemical composition. Bioactivity improved through the ablation phenomenon's enhanced titanium oxide layer and cleaner surface. These alterations are essential to the long-term viability of dental implants because they may shorten healing periods and enhance patient results.
2. On titanium implants, DAE produces micro-rough surfaces that have been demonstrated to hasten osseointegration. This quality is essential in situations where quick bone healing and implant stability are required. The enhanced surface characteristics may improve the clinical efficacy of dental implants by promoting bone apposition and enhancing osteogenic cell adhesion.

Recommendation

1. Clinical studies with larger patient populations for long time needed for implant with fibre laser irradiation surface treatment.
2. More studies are needed, mentioning detailed parameters for both treatments to have applicable research.
3. The combination between these two surface treatments, both fibre laser irradiation and DAE in the literature is lake, so there is a need to experiment with the mixed of these two methods on the same surface.

Table (1): PICOS format of the question used in this systematic review.

Component	Description
Participant	Studies focusing specifically on titanium dental implants.
Intervention	Fibre laser irradiation or dual acid etching surface treatments of titanium dental implants.
Control	Machined surface (untreated) of titanium dental implants.
Outcome	Assessment of the implant's surface properties (like roughness, topography, wettability, surface chemistry, corrosion resistance, and bioactivity) and their effect on osseointegration.
Study Design	In vitro, in vivo, and clinical studies.

Table (2): Fibre laser parameters (wavelength (nm), power (W), pulse energy (mJ), frequency (Hz), energy density (J/cm2), and scan speed (mm/s)) and results of surface properties (topography, roughness, wettability, surface chemistry, and corrosion resistance), and biological response.

	References	Comparative method used/ Ti alloy classification	Laser type/ parameters	Results of surface properties	Results of biological response
1	Çelen(23)	Different laser parameters/ Cp titanium	Q-switch fibre laser / 1064nm, (1.2, 1.7, 1.8) mJ, (100, 150, 50) mm/s	Topography revealed that the surface pattern had artificial lotus leaves shape.	N/M
2	Çelebi et al.(24)	Three laser application techniques (unidirectional,2D and 3D	Pulsed Erbium fibre laser/ 20W, (0.1, 0.5) mJ,	Different surface topographies were created, the microstructure and microcracks were	The 3D crosshatching texture increase the adherence of cells compared to

		crosshatching were used to evaluate cell attachment/ Cp Ti grade 4	(30000, 40000) Hz, (100, 1000, 520) mm/s	observed on Ti surface. The roughness of unidirectional texture had the greatest value than 2D and 3D crosshatching.	unidirectional and 2D crosshatching.
3	Pires et al. (25)	Using two Ti materials/ Cp Ti grade 2 and Ti-15Mo alloy	Pulsed Yb Fibre Laser/ 20-35kHz, 1.9 J/cm^2, 0-200mm/s	The topography revealed irregular-shaped cavities and a typical micro structured surface with large depressions. The contact angle for both materials was 0^0. TiO_2 was detected on laser treated surfaces with no contamination.	Enhancing the biological response of the laser treated surfaces through increasing cell differentiation and proliferation.
4	Xue et al. (26)	Comparing treated and untreated surfaces of the same Ti alloy/ Ti-20Zr-10Nb-4Ta alloy	Pulsed wave 15W Fibre Laser/ 1064nm, 11.4W, 100kHz, 700mm/s.	The topography showed rougher groove morphologies and uniform ripples are observed at the bottom of the grooves. Increase roughness of laser irradiated surface. The contact angle is closer to that of untreated surface. The surface chemistry indicate that the outermost oxide layer is mainly composed of TiO_2 enriched with (O and C) and also the oxidation of Zr and Nb on the surface of the TZNT alloy. The corrosion resistance of the alloy was improved.	The biological response of the treated surface is enhanced and induced obvious orientation for cell growth.
5	Wen et al. (27)	Two different environments (Ar and N_2)/ Ti-10Mo alloy.	Yb fibre laser/ 1070nm.	The topography showed vertical lines with unique corrugated features. Increased surface roughness. The surface chemistry revealed the formation of a β-Ti- rich layer and a TiN layer. Improved corrosion resistance.	Enhanced biological response and the cell density of laser-N_2 sample is higher than that of the laser-Ar sample.
6	Kumari et al.(28)	Using two laser devices/ Ti-6Al-4V alloy	Fiber Laser/ 5W, 80kHz, 800mm/s	The topography revealed the presence of random grooves, micro porosities, and nano spherical particulates. Increased surface roughness value. There is a significant improvement in wettability. Increase the corrosion resistance of the	Increases the bioactivity in terms of area fraction of apatite deposition.

				treated surface.	
7	Łęcka et al. (29)	Different laser parameters (two diameter of the laser beam (40, 160))/ Cp Ti grade 2	Yb: glass fiber laser/ 1062nm, (5,18) W, 80kHz, (160, 110, 65, 500, 370, 220) mm/s	The topography revealed the presence of microcracks. Increase the surface roughness and the high value with 160µm laser beam width. Increased wettability of all laser treated samples. The surface chemistry revealed the formation of an oxide layer on the treated surface of Ti (mainly TiO_2 and Ti_2O_3). The corrosion resistance is highly increase with 40µm but is significantly worse with 160µm.	N/M
8	Rodríguez et al. (30)	Using fully-dense and porous samples/ Cp Ti grade 4	Yb-doped fibre laser (femtosecond laser)/ 1040nm, 49.7µJ, 100kHz, 21.98J/cm2, 960mm/s.	The topography revealed clusters of micro holes and columns/ nanometric structures across the entire surface. Laser creates hierarchical triple structure with a heterogeneous height and grainy texture. There were increased in the roughness values.	A clear improvement in cell proliferation in the fibre laser modified disc.
9	Al-Khafaji et al.(31)	Two surface structure design (dots and grooves) in three different laser scans / Cp Ti grade 2	Fibre laser CNC machine / 1064nm, 20W, 7000mm/s	The surface showed micropits and microgrooves topography. Increase roughness when laser scan increase, although the dot design shown best result than groove design for the same laser scan. Wettability increased (decrease WCA).	N/M
10	Hussein et al.(32)	Different laser parameters/ Cp Ti grade 2	Fibre Optic Laser/ 1064nm, (20, 25, 30)W, 1kHz, (5, 10, 15)mm/s	A homogenous texture is observed with a hatch configuration over multiple length micron scales with microgrooves. Increased roughness values. The surface chemistry confirms the formation of Ti oxide layer.	N/M
11	Al-Khafaji et al.(33)	Two surface structure design (dots and grooves) in three different laser	Fibre laser CNC machine/ 1064nm, 20W,	The surface topography exhibits a highly uniform homogenous clear dots and continuous grooves. The surface chemistry	N/M

		scans/ Cp Ti grade 2	10000mm/s	showed increase in TiO2 layer for both designs and laser scan	
12	Veiko et al. (34)	Comparing three different reliefs on the Ti surface (grid, open groove, and close groove/ Ti6Al4V alloy	Yb pulsed fibre laser (nanosecond laser) / 1064nm, (3, 8.18, 2.65) W, (1.6, 60, 20) kHz, (5, 200, 15) mm/s	The surface topography showed three types of relief: two types of continuous relief (open and close groove) and one discontinuous relief "grid". The roughness is increased. The grid topography has the highest roughness 11µm than the open and close topography (both 3µm). The surface wettability had changed from hydrophilic to super hydrophilic.	The cell proliferated perfectly in all reliefs. However, the maximum number of cells on day 20 was found on the surface of the open grooves.
13	Eghbali et al. (35)	Different frequencies and groove distance/ Ti6Al4V alloy	Fibre engraving laser device/ (20, 80, and 160) kHz, 200mm/s	The surface topography showed regular patterns of parallel rows, also reveals lots of spherical grains and cavities around the grooves. Roughness values is higher than the untreated sample but when increasing the grooving distance, it decreased. The wettability is decreased when increasing the grooving distance. The surface chemistry revealed that the amount of Al and V elements on the surface was decreased.	The cytocompatibility is enhanced specially for the samples engraved with a higher groove distance.
14	Santos et al. (36)	Three different types of surfaces / Cp Ti grade 4	Yb pulsed fibre laser/ 20W, 140mJ, 20kHz	The topography showed homogeneous rough surface. The roughness values increased. The wettability had increased. The surface chemistry showed the presence of oxides and nitrides (TiN).	N/M
15	Veiko et al. (37)	Several biomimetic topographies of various shapes on	Pulsed Yb fibre laser (nanosecond laser) /	Three types of topographies (irregular structure, slots and grooves structures) and	The groove topography had the highest BIC parameters and

		the Ti surfaces / Ti6Al4V alloy screw shape implant	1064nm	nano porous topography. The surface chemistry showed a significant enrichment of the surface with oxygen compared to non-treated samples	contained the highest number of mature osteocytes.
16	Alawadi et al. (38)	Comparing two Ti materials/ Cp Ti grade 2 and Ti-13Nb-13Zr alloy.	CNC fibre laser/ 1064nm, 30W, 300mm/s	The topography reveals a zigzag lines design and creates deep trenches and holes marking the lines. Increase roughness values. Increase wettability.	N/M
17	Alawadi et al. (39)	Comparing two Ti materials/ Cp Ti grade 2 and Ti-13Nb-13Zr alloy.	CNC fibre laser/ 1064nm, 30W, 300mm/s	The topography reveals a zigzag lines pattern. The surface chemistry revealed formation of TiO_2 on laser groups. The higher corrosion resistance observed with laser groups of both materials.	N/M
18	Al-Khafaji et al. (40)	Comparing three different surface treatment methods/ Cp Ti grade 2	CNC fibre laser/ 1064nm, 20W	Obtained an improved corrosion resistance on the laser treated group.	N/M

Ti: titanium, Cp: commercial pure, N/M: not mentioned, mm: millimeter, um: micrometer, nm: nanometer, W: watt, mJ: milli Jole, uJ: micro Jole, Hz: Hertz, s: second, 2D: two dimensional, Yb: Ytterbium, CNC: computer numerical control, WCN: water contact angle, Al: aluminum, V: vanadium, BIC: bone contact to implant.

Table (3): Dual acid etching DAE parameters (acid type, acid concentration (%), temperature of acid(C^0), and duration of treatment(time)) and results of surface properties (topography, roughness, wettability, surface chemistry, and corrosion resistance) and biological response results after DAE surface treatment.

	References	Comparative method used/ Ti classification	DAE Parameters	Results of surface properties	Results of biological response
1	Ramaglia et al. (41)	Compare the HGF cells response on both machined and DAE surfaces/ Cp Ti grade 4.	HF (15%), and mixture of ($HCl+H_2SO_4$) (6:1)/ $60C^0$-$80C^0$/ 3 to 10 min.	The surface roughness had minimally rough surface 0.5 µm. The water contact angle was increased, so reduced hydrophilicity obtained.	The etched surface promoted a higher cell proliferation and differentiation improving the biological behavior of HGFs.
2	Yoo et al. (42)	Evaluating the biological response of three different Ti surface / Ti6Al4V alloy (implant screw).	N/M	N/M	Increased bone to implant contact for DAE implants.
3	Jemat et al. (43)	Investigating the effect of	Mixture of H_2SO_4 (95%)	Topography revealed the presence of micropits and	N/M

		different types of acids on physical properties/ Ti6Al4V alloy.	and HCl (36%)/ At room temperature/ 45 min.	micropores with homogenous surface with peak and sharp edges. The surface roughness value is low. The surface chemistry showed that the etched surfaces covered by thin oxide layer which is contains TiH2.	
4	Nádai et al. (44)	Two Ti materials and different etching time/ Cp Ti grade 2, grade 5 Ti6Al4V alloy.	Mixture of HF (9%) and HNO_3(12%)/ $30C^0$ / 15 to 600 sec.	The surface topography became homogenous and microrough surface on Ti grade2 and grade5. By increasing etching time, the surface roughness was not significantly smoother and grade 5 surface showed that the surface is rougher than at grade 2 samples.	N/M
5	Faverani et al. (45)	Several treated surfaces/ Ti-6Al-4V alloy	Mixture of HNO_3, H_2SO_4, and HCl	The topography exhibited uniformly pitted surfaces. Increased surface roughness. Good corrosion resistance results.	N/M
6	Zhao(46)	Three different Ti surfaces/ Ti6Al4V ELI alloy	N/M	The topography showed micropits throughout the surface, characterized by prominent peaks and valleys. The surface roughness was increased with 1.36 µm. The wettability increased with hydrophilic surface.	Increase cell growth and fibroblast cells have an irregular shape and formed even and higher surface coverage.
7	Ogawa et al. (47)	Several methods of modification were introduced/ Cp Ti grade 2	-Mixture of HCl (0.1mol/L) and H_2O_2 (8.8mol/L) at 80^0 C during 20 min. -Mixure of (H_2SO_4 + H_2O_2) at 25^0 C for 2 h.	Greater corrosion stability results especially with HCl and H_2O_2.	N/M
8	Del Fabbro et al. (48)	Several methods of modification were introduced/ Ti6Al4V alloy	HF and mixture of (HCl+H_2SO_4)/ 60-$80C^0$/ 3-10 min.	The topography revealed surface irregularities in the micrometric and nanometric scale. The roughness was moderately rough surface. The surface chemistry	After three months, inflammatory cells were clearly detected around implants with DAE surface also

				showed the presence of Ti, Al, and V (characteristics of alloy)	made of Ti alloy. There was good degree of osseointegration at cortical bone but had the lower value of BIC.
9	Mangano et al. (49)	Compared the early bone response to implants with DAE and machined surface/ Cp Ti grade 4	(H_2SO_4, H_3PO_4, HCl, and HF) in two different acid baths/ NM	The surface roughness was increased with moderately rough surface 1.12 µm.	The DAE surface increased the peri implant endosseous healing properties in the native bone of the posterior maxilla.
10	Nazarov et al. (50)	Two types of etchants with different periods of time / Cp Ti grade 4	Mixture of (H_2SO_4 + H_2O_2) at 20^0 C/ 5, 15 min, and 1, 2, 6, and 24 h.	The topography considered the formation of nano and microstructure and sponge- like structure. Increase roughness values. Surface chemistry revealed the formation of oxide layer (oxidation leading to oxides TiO_2, Ti_2O_3, TiO, and formation of low stability sulfates $Ti(SO_4)_2$ and $TiOSO_4$.	N/M
11	Cordeiro et al. (19)	Three different Ti materials/ Cp Ti, Ti6Al4V and Ti-Zr alloy	H_2SO_4 and HCl/ 1h and 50 min.	The topography showed an irregular and complex micro topography and a porous surface with pits. There was a significant increase in the average roughness of all materials. All materials showed predominantly hydrophilic behavior, having WCA lower than 900. The surface chemistry showed that the alloying elements (V and Zr) were increased. An increase in in corrosion resistance for treated surfaces especially Ti-Zr alloys.	Numerous filopodia extensions towards the holes of DAE surfaces suggested a strong cell attachment.
12	Gehrke et al. (51)	Effect of microgrooves on the process of osseointegration compared to other two different surfaces/ Cp Ti grade 4.	HF (9.0%), and mixture of (H_2SO_4 30% and HF 0.09%)/ At room temperature/ 45s for HF and 30 min for the	The topography showed a regularly distributed microgrooves, with a deep and regular morphological pattern with small pores. The roughness was increased slightly (minimally rough surface). The wettability was	With microgrooves superficial condition can accelerate and increase the growth of bone tissue on the surface of the

			mixture	decreased. The surface chemistry showed high levels of Ti, without presence of other metal ions or contaminants.	implant.
13	Marenzi et al. (52)	Two different types of surface treatment methods/ Cp Ti	Mixture of 2% HF and 10% HNO_3	The topography revealed irregular texture characterized by the presence of deep valleys and high peaks. Improve surface roughness.	N/M
14	Velasco-Ortega et al. (17)	Long term evaluation of treatment by the early loading of etched surface implant/ TSA Defcon implants	HF and HNO_3 / N/M	The topography showed an irregular microtopography characterized by the presence of deeper valleys and higher peaks. Higher values of roughness	Successful bone integration to implants.
15	Diomede et al. (53)	Two different types of titanium surfaces/ Cp Ti grade 4	N/M	N/M	Increased cell growth, cell adhesion, improved osteogenic and angiogenic events as well osseointegration process.
16	Nicolas-Silvente et al. (54)	Nine different implant systems with different surface treatment were evaluated/ N/A	N/M	Minimally rough surface (0.79µm). The surface chemistry showed the lowest percentage of carbon with 40.2% among other surfaces.	N/M
17	Doe et al. (55)	Several treated surfaces/ Cp Ti	Mixture of 30% ultrapure water, 20% HCl, and 50% H_2SO_4 at 70^0 C for 30 min.	Increase surface roughness.	Increased bone to implant contact and improve osseointegration.
18	Ferro et al. (56)	Several methods of surface treatment of Ti/ Cp Ti grade 4	HCl+H_2SO_4	The topography revealed that numerous irregularities on the surface and the presence of micropores. Minimally rough surface 0.9 µm.	There was a difference in the cell adhesion during the period 1, 3, 7 days.

Ti: titanium, Cp: commercial pure, N/M: not mentioned, mm: millimeter, um: micrometer, nm: nanometer, W: watt, mJ: milli Jole, uJ: micro Jole, Hz: Hertz, s: second, 2D: two dimensional, Yb: Ytterbium, CNC: computer numerical control, WCN: water contact angle, Al: aluminum, V: vanadium, BIC: bone contact to implant.

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