TITANIUM ALLOY ORTHODONTIC MINI-IMPLANTS: SCANNING ELECTRON MICROSCOPIC AND METALLOGRAPHIC ANALYSES

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ABSTRACT
Anchorage control is one of the determining factors of successful orthodontic mechanics. In mini-implants, fractures due to placement and removal have been related to implant design and titanium alloy quality. This study assessed the topography and microstructure of five brands of mini-implants (Neodent, SIN, Morelli, Conexão, Foresta Dent). Scanning electron microscopic analyses of the head, transmucosal neck, threaded body, and tip were performed to assess implant design and manufacturing defects (n=3/group). Metallographic analysis of longitudinal sections (n=15) and cross-sections (n=15) was performed under conventional light microscopy according to international standards of "American Society for Testing and Materials". The results showed significant differences in mini-implant design. Surface irregularities in the threaded body and tip were observed. Microstructural analyses revealed an alpha/beta-phase grain structure, in compliance with the ETTC-2 ("Technical Committee of European Titanium Producers" –2nd edition). No structural defects were detected. We conclude that differences in mini-implant design and the presence of surface irregularities may influence the effectiveness of orthodontic anchorage.

Key words: *orthodontics; dental implantation; titanium.*

MINI-IMPLANTES ORTODÔNTICOS DE LIGA DE TITÂNIO: ANÁLISES AO MICROSCÓPIO ELETRÔNICO DE VARREDURA E METALOGRÁFICA

RESUMO
O controle da ancoragem é um dos fatores decisivos no sucesso da mecânica ortodôntica. Fraturas devido ao estresse de inserção e remoção de mini-implantes são associadas ao design das peças e à qualidade da liga de titânio. O presente estudo analisou a topografia e a microestrutura de cinco marcas de mini-implantes (Neodent, SIN, Morelli, Conexão, Foresta Dent). Análise ao microscópio eletrônico de varredura da cabeça e perfil transmucoso, porção rosqueável e ponta ativa foi realizada com o propósito de avaliar o design e defeitos de fabricação (n=3/grupo). A análise metalográfica baseou-se nas normas internacionais da "American Society for Testing and Materials" e revelou a microestrutura em cortes longitudinais (n=15) e transversais (n=15) por meio do microscópio óptico. Os resultados demostraram que os mini-implantes apresentam diferenças significativas no design. Irregularidades superficiais na porção rosqueável e na ponta ativa foram também observadas. A análise da microestrutura revelou uma estrutura de grãos fases alfa e beta distribuídas de acordo com os padrões definidos pelas normas ETTC-2 ("Technical Committee of European Titanium Producers" – 2ª edição). Além disso, não foram detectados defeitos na estrutura interna das ligas. Conclui-se que diferenças no design dos mini-implantes e a presença de irregularidades superficiais podem influenciar na efetividade da ancoragem durante o tratamento ortodôntico.

Palavras-chave: *ortodontia; implante dentário; titânio.*

INTRODUCTION

Orthodontics is based on the exertion and control of forces acting on the teeth and supporting structures. Therefore, control of anchorage is essential for the success of orthodontic treatment[1].

Traditional orthodontic anchorage depends on patient compliance. Furthermore, the number or quality of teeth is often insufficient for effective anchorage[2]. Therefore, several anchorage devices have been used in recent decades. Prosthetic implants, plates, and onplants have been replaced with mini-implants because they eliminate the need for invasive surgical procedures, high cost, placement site limitations, and considerable time for osseointegration[3].

Mini-implants are popular because of their ease of insertion and removal, less discomfort for patients, possibility of immediate loading, high versatility, and low cost[4-6]. Clinical and laboratory outcomes, however, have shown failure rates of 10 to 30%, mostly related to inflammation of peri-implant tissues, characteristics of soft tissues, and mini-implant placement site[7-9]. Screw diameter, length, thread form, presence of flutes, and screw material have also been implicated in poor primary stability of these devices[10-13].

The optimal material of mini-implants would exhibit excellent corrosion resistance, biocompatibility, and sufficient mechanical strength to resist placement and removal[14]. Titanium alloys have been used in these devices. The use of vanadium and aluminum have significantly enhanced their performance and mechanical properties[15]. Nevertheless, studies on the internal microstructure of mini-implants rare in the literature[14-16].

Because of the diameter and length restrictions of mini-implants, optimal shape design is important for primary stability. The strength resistance of a titanium alloy depends on its microstructure, which is influenced by the composition, heat treatment, and machining processes of the mini-implant[17]. Thus, studies analyzing the topography and microstructure of mini-implants are essentially important. The objective of the present study was to analyze the topographical and microstructural features of mini-implants used for orthodontic anchorage.

MATERIALS AND METHODS

Topography and microstructure were analyzed on Ti-6Al-4V (Grade 5 titanium alloy) self-drilling orthodontic mini-implants from five different dental implant manufacturing companies (four Brazilian and one imported). They were allocated into five groups: Group 1 – Neodent® (Curitiba, Paraná, Brazil); Group 2 – SIN® (São Paulo, São Paulo, Brazil); Group 3 – Morelli® (Sorocaba, São Paulo, Brazil); Group 4 – Conexão® (Arujá, São Paulo, Brazil); and Group 5 – Foresta Dent® (Pforzhein, Baden-Württemberg, Germany).

Scanning electron microscopy (SEM) analysis was conducted to obtain a descriptive analysis of implant design and detect potential manufacturing defects. Three mini-implants of each of the five brands were analyzed. The implants were bonded to aluminum stubs (Sigma Chemical Co., St. Louis, Missouri, USA) with cyanoacrylate adhesive (Super Bonder Gel, Loctite, Diadema, São Paulo, Brazil) and immediately analyzed under high-vacuum SEM (Philips XL 20, FEI, Eindhoven, The Netherlands) at 20kV accelerating voltage. Images of the screw head, transmucosal neck, threaded body, and tip were analyzed at 50x, 100x, and 200x magnification.

Metallographic analysis was conducted to detect discontinuities and to assess the presence of alpha- and beta-phase titanium. The methodology was based on the “American Society for Testing and Materials” (ASTM International). The standards applied were ASTM E3-01 (Standard Guide for Preparation of Metallographic Specimens)[18], ASTM E407-99 (Standard Practice for Microetching Metals and Alloys)[19], and ASTM E7-03 (Standard Terminology Relating to Metallography)[20]. Six mini-implants (three in longitudinal section, three in cross section) from each of the five brands were analyzed.

For longitudinal sections, the samples were cold-embedded in methyl methacrylate polymer before being sectioned lengthwise. The mini-implants were ground and polished with a series of silicon carbide abrasive sheets - 220, 320, 400, 600, and 1200 grit (3M, Sumaré, São Paulo, Brazil) under water. The samples were polished in a DP-10 sander (Panambra, São Paulo, São Paulo, Brazil), using diamond abrasive compound (3M, Brazil) with 1- and 2-mm grains. The longitudinally sectioned and polished mini-implants were etched in a solution of 10mL HF, 5mL HNO_3, and 85mL H_2O (Kroll’s reagent) for 20 seconds, dried with hot air, and analyzed under light microscopy (Union MC 85800, OptiTec Ltd., Japan) at x50 and x400 magnification.

Cross sections were obtained at TORK (Controle Tecnológico de Materiais Ltda, São Paulo, São Paulo, Brazil). Samples were cold-embedded in acrylic resin. Metallographic analysis was based on the ISO 5832-3 standard (Implants for surgery - Metallic materials - Part 3), and the alpha/beta phases were compared with the European Technical standards (ETTC-2) published by the Technical Committee of European Titanium Producers. The mini-implants were sectioned with a circular table saw (Arotec, São Paulo, São Paulo, Brazil) and a cutting disc (Norton, Worcester, Massachusetts, USA). The–specimens were sanded in a round device with silicon carbide abrasive sheets - 150, 220, 320, 400, and 600 grit (3M, Brazil), on a tabletop grinding machine, using water as a lubricant to obtain a flat, homogeneous surface. The specimens were then polished in a sander with 6-µm and 3-µm diamond abrasive compound and buffed with 1-µm diamond compound. The cross-sectioned specimens were etched with a solution composed of 6 g NaOH, 60 mL H_2O, and 10 mL H_2O_2 for 20 seconds and dried with hot air. This process revealed the microstructure of the mini-implants, in which an effective contrast between alpha and beta phases was observed. The cross sections were examined under light microscopy (OPTON / TNM-07 PL, Cotia, São Paulo, Brazil) at x200 magnification.

RESULTS

The mini-implants exhibited significant differences between brands in screw head and transmucosal neck; pitch and shape of threads; and active tip design (Fig. 1).

Surface irregularities can result from machining process, polishing defects, crystal growth deposits, and areas of detritus. The greatest amount of surface irregularities and detritus was found on the tips of Groups 1, 2, and 3. The best surface finish along the threaded body was found in Groups 1 and 5. Mini-implants in all groups had adequate surface finish and no evidence of irregularities on the screw head or transmucosal neck (Fig. 1).

Despite the differences in the size of the orthodontic accessory on the screw head, they all had uniform structure and good surface finish. In Groups 1, 2, 3 and 4, the accessory was in the shape of an orthodontic button, whereas Group 5 mini-implants had bracket-shaped screw heads (Fig. 1).

Mini-implants in Group 4 had a greater number of threads and flutes at the tip and a screw head diameter equal to that of the transmucosal neck. In Groups 1, 2, 3, and 5, the screw head and transmucosal neck had different diameters. Although all mini-implants were of the self-drilling variety, those in Groups 1, 3 and 5 had sharper tips (Fig. 1).

Longitudinal sections were assessed to detect defects in the internal microstructure of each mini-implant, whereas cross-sections were compared against the ETTC-2 regarding the distribution of alpha and beta phases in the alloy.

There were no visible imperfections in the inner structure of any mini-implants, and no internal defects were detected on the longitudinal sections.

The mini-implants had a fine microstructure composed of an alpha matrix into which spheroidal beta-phase particles were dispersed. On cross sections, the internal microstructure of the alloys was consistent with ETTC-2 standard class A1. Alpha phase titanium appears light, whereas beta-phase granules appear darker. The small granule size of both phases and balanced alpha/beta ratio are indicative of high internal structure quality (Fig. 2).

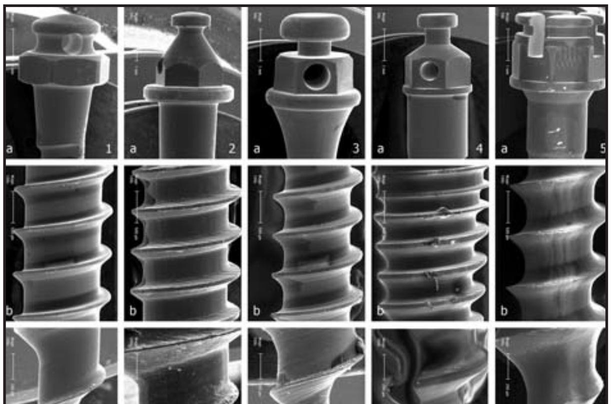

Fig. 1: Head and transmucosal neck (a) threaded body, (b) and active tip, (c) of mini-implants in the Neodent® (1), SIN® (2), Morelli® (3), Conexão® (4), and Foresta Dent® (5) groups.

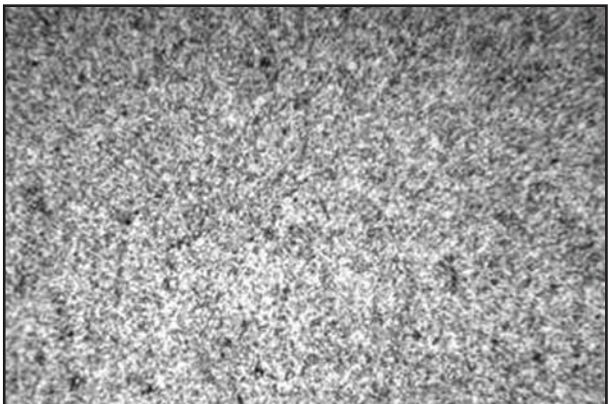

Fig. 2: Photomicrograph showing the microstructure of the mini-implants (cross section)

DISCUSSION

We found significant differences in screw head, threaded body, and tip design between the five brands of mini-implants. Furthermore, SEM analysis showed surface irregularities and detritus, particularly at the implant tip. Metallographic analysis did not show any defects in the microstructure. All mini-implants tested met the European standard for titanium alloy production.

Mini-implants are an effective and very well tolerated tool for skeletal anchorage, and have become the gold standard for orthodontic biomechanics in adults[2]. They are available in a variety of shapes, diameters, lengths, and titanium alloy compositions. However, it bears stressing that failure has been reported during mini-implant placement and removal. Mini-implant fractures are usually due to torsional strain caused by their small diameter[7,15,21]. Reicheneder et al.[22] reported that different mini-implant systems showed comparable elementary composition. They stressed that differences in mechanical properties can be attributed to mini-implant design, and that implant morphology plays an essential role in ensuring primary stability.

In our study, the surface defects found in most samples, particularly at the active tip, may be caused by the machining process. These defects may be a starting point for electrochemical degradation processes that can alter the surface finish of the implant and its resistance and other material properties[23]. According to Sebbar et al.[24] improvements in the surface treatment of mini-implants could improve their corrosion resistance. Mini-implants in Group 5 had fewer surface irregularities at the tip and better polish along the threaded body.

The machining process determines the surface finish of the piece. Machining leads to a rough surface. Therefore, the biocompatibility of the surface texture has major influence on the type and progression of reactions in the tissues adjacent to the implant surface. Furthermore, changes in surface morphology that may occur during the sterilization process and mechanical damage that may be sustained during mini-implant placement and removal may induce changes in osteoblast growth and differentiation[25,26].

Studies have also analyzed changes in mini-implant design that might lead to improvements in the mechanical properties[11]. A greater number of threads and a finer pitch in the implant are associated with greater mechanical locking ability, enhanced resistance during mini-implant placement, improved resistance to displacement, and improved primary implant stability[8]. Mini-implants in Group 4 may improve the distribution of applied forces because they have a greater number of threads. Furthermore, the presence of flutes may be linked to greater fracture resistance, as it prevents concentration of excessive strain in the adjacent tissues[8,26]. Conversely, thread design may also interfere with the distribution of strain under load[11]. Hence, further studies are required to ascertain the influence of design on the mechanical properties of mini-implants.

Lee et al.[27] found that many undesirable outcomes are attributable to the design of mini-implants. They claim that a coarsely finished or poorly designed mini-implant active tip may compromise final implant placement and primary stability. All mini-implants we tested were of the self-drilling variety, and those in Groups 1, 3 and 5 had the finest and sharpest tips, which suggests greater ease of placement without pilot hole drilling. The diameter of the mini-implant head is an important design factor. It should be wider than the transmucosal neck to prevent overgrowth of soft tissues. All implants had this design feature, except for those in Group 4. Casaglia et al.[12] showed that small transmucosal neck diameter is a site of increased fragility. The authors detected microfissures and grooves on the surface and concluded that these irregularities may predispose to mini-implant fracture.

Most mini-implants are made of Ti-6Al-4V (ASTM Grade 5 titanium alloy). This alloy has greater mechanical resistance than pure titanium and is more appropriate for small-diameter devices. Furthermore, its lower bioactivity facilitates implant removal because of less osseointegration[18].

Titanium alloys must be free of external irregularities and internal imperfections to avoid interference with fracture resistance, mechanical retention, displacement resistance, and primary stability[16]. Our metallographic analysis did not reveal any internal defects, corroborating the findings of Cotrim-Ferreira et al.[15] and Eliades et al.[16].

The alpha phase of titanium alloys is a soft alloy showing high resistance and tensile strength, but low ductility. Alpha-stabilizing elements increase the temperature range at which the alpha phase remains stable. The beta phase, in turn, has superior forming and fatigue resistance, but is highly vulnerable to atmospheric contamination. Beta stabilizers make the beta phase stable at low temperatures[18].

The matrix of all mini-implants assessed contained beta and alpha titanium, which indicates that the small amount of vanadium in the alloy was sufficient to retain significant amounts of beta-phase titanium, thus enhancing the properties of the alloy, as demonstrated by Iijima et al.[14].

All mini-implants complied with the ETTC-2 standards, namely in class A1. Cotrim-Ferreira et al.[15] found that the microstructure of Conexão® brand implants was class A9, showing differences in hardness, resistance, and elastic modulus because of different alpha-beta phase ratio. However, this may not interfere with mechanical resistance, as alloys of any class from A1 through A10 can be used for mini-implant manufacturing according to the ETTC-2 standards.

Despite the advantages of titanium alloy mini-implants, practitioners must be aware of the topographic and microstructural features of mini-implants, since they influence the effectiveness of orthodontic anchorage. Orthodontic treatment depends on reliable and effective anchorage. Primary stability, mechanical resistance, and clinical performance of mini-implants, in turn, depend on their topographical and microstructural characteristics.

The present study concluded that the orthodontic mini-implants assessed exhibited significant differences in the design of the screw head, transmucosal neck, threaded body, and active tip. Furthermore, surface irregularity and debris were found in all groups, particularly at the active tip. Conversely, no internal defects were detected, and all groups complied with the international standards for mini-implant manufacturing. Further studies of orthodontic mini-implants should prioritize topographic and microstructural analysis combined with mechanical testing.

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