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Original Article

Is fatigue mechanism implicated in intraoral fracture of narrow dental implants? A thorough retrieval analysis of two failed implant fixtures retrieved from a single patient

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ABSTRACT

Purpose: This study aimed to perform a thorough failure analysis of two fractured narrow dental implants after medium-term in vivo use.

Materials and methods: The top parts of two fractured Narrow Dental Implant (NDI) fixtures were retrieved from two different locations at two different times from the same patient. The NDI-specimen-1 was 12-months in service while the NDI-specimen-2 was 17-months in service. In both cases, the top parts of the fractured NDI fixtures that were attached to prosthetic components were retrieved and subjected to thorough, non-destructive and destructive testing.

Results: Light Microscopy (LM) and Scanning Electron Microscopy (SEM) revealed that both the retrieved fractured NDIs failed because of fatigue, characterized by beach and ratchet marks. Macroscopic examination revealed that fatigue cracks initiated at the internal thread surfaces of the implants and propagated around them until final fracture. Both samples fractured near the end of the retaining screw and followed the root of the internal thread. Optical and SEM analyses revealed a uniform distribution of irregularly shaped grains (diameter = 2 to 5 μm). X -ray Energy Dispersive Spectroscopy (EDS) analysis showed that the NDI-specimen-1 was made using Ti-14%Zr with a Vickers Hardens (HV) of 288 ± 5.

Conclusion: Since the fracture occurred by a fatigue; thus, an increase in fatigue resistance will be beneficial for the longevity of NDI.

1. Introduction

Implant therapy has a long history of successful rehabilitation with Standard Dental Implants (SDI) for single, partial, or full dental implant retained and supported prosthesis (Brugger et al., 2015). In recent years, a new class of implants, commonly known as narrow dental implants (NDI), has been introduced. The implants of this class have narrow diameters (<3.75 mm) (Klein et al., 2014) and provide dental clinicians with additional therapeutic options. In cases where the available bone tissue does not permit the placement of a standard implant, NDIs can be used successfully, avoiding the need for surgical bone grafting (Davarpanah et al., 2000, Flanagan 2008, Chiapasco et al., 2012, Galindo-Moreno et al., 2012). Recent studies have estimated that approximately 10% of horizontal bone augmentation techniques can be omitted by employing NDIs (Papadimitriou et al., 2015).

NDIs appear promising as their survival rates are comparable to SDIs (Zinsli et al., 2004, Arisan et al., 2010, Malo and de Araujo Nobre 2011, Ioannidis et al., 2015, de Souza et al., 2018, Marcello-Machado et al., 2018) with an optimistic estimated survival rate higher than 95% after 11 years (Malo and de Araujo Nobre 2011). Despite the favorable estimation of their longevity, previous reports have pointed out that their strength is approximately 75% compared to SDIs (Olate et al., 2010), increasing the risk of fatigue failure under clinical conditions (Allum et al., 2008). Other studies employing finite element analysis indicated that NDIs exert higher stress and strain at the *peri*-implant bone than SDIs, affecting the rate of bone resorption (Baggi et al., 2008, Ding et al.,

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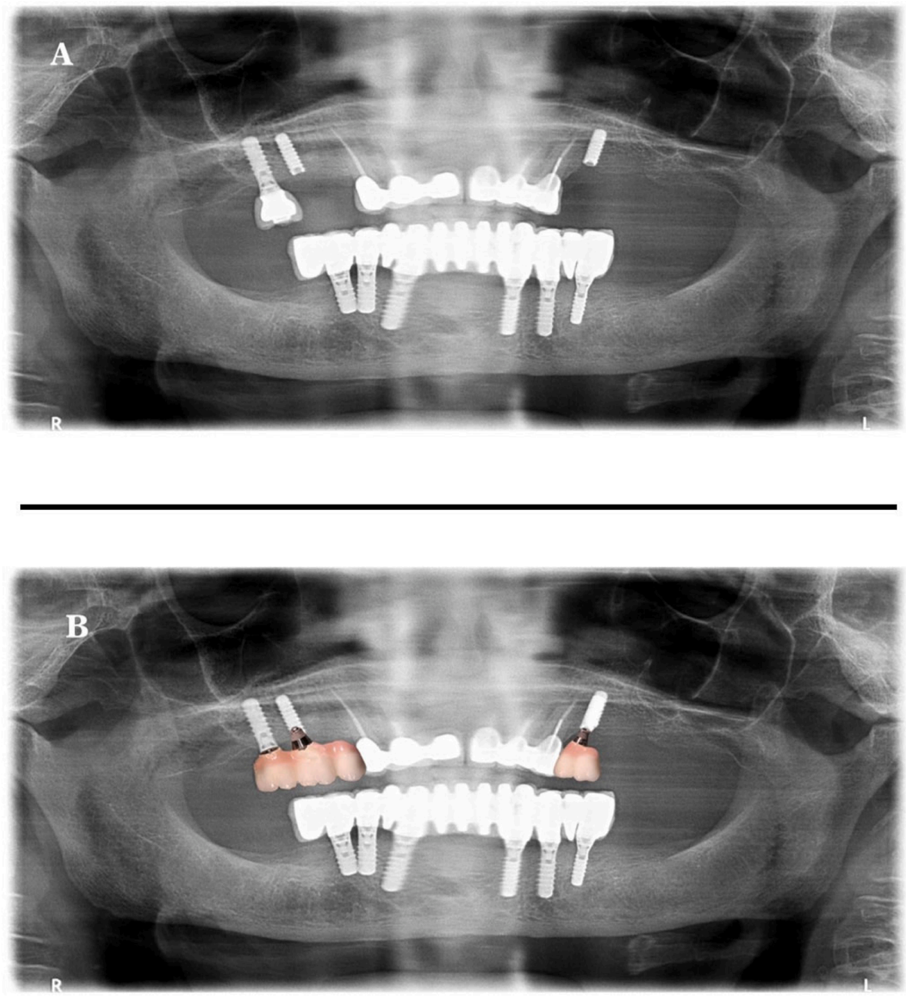

Fig. 1. (a) Panoramic X-ray (OPG) of the patient showing the two fractured narrow dental implants (NDIs) in the area corresponding to #15 and #24. In (b), the retrieved FPD prosthesis with cantilever pontics is superimposed on the OPG to illustrate the exact position of the fixed prosthesis in the patient's mouth before NDI fracture.

2009). This complication may be noticed by clinicians and may explain why NDIs are not used to restore areas, such as the posterior region, where high masticatory stresses are anticipated (Galindo-Moreno et al., 2012). To reduce fatigue failure rate, the utilization of more durable Ti alloys instead of commercially pure (cp)-Ti is always an option. Recently, Ti-Zr systems have attracted the interest of researchers mainly because of their favorable biocompatibility and corrosion resistance, in addition to the beneficial effect of Zr on the mechanical properties of experimental binary formulations of Ti-xZr (Kobayashi et al., 1995, Ho et al., 2009, Grandin et al., 2012, Correa et al., 2014). The outcome of this study was that Ti-xZr alloys can produce NDIs with a mechanical strength up to 40% higher than that of cp-Ti (Grade 4) (Grandin et al., 2012). More specifically, for Ti-15 (wt%) Zr, tensile tests showed that the yield strength was approximately 10% higher than that of the cp-Ti-Grade 4 and the tensile strength was 10–15% higher with comparable elongation after fracture (approximately 20%) (Medvedev et al., 2016). Impact tests showed that the Ti-15Zr alloy required more energy per unit area to fracture than the cp-Ti-Grade 4, and fatigue tests showed that the endurance limit of Ti-15Zr was approximately 30% higher than that of cp-Ti-Grade 4. The increase in mechanical properties was attributed to solid solution strengthening, increased grain boundary strengthening, and increased work hardening (Medvedev et al., 2016). This alloy was named Roxolid® and is commercially available in the dental market as NDIs by Straumann.

Although Ti-15Zr has better mechanical properties than cp-Ti-Grade 4, there is no clinical evidence to prove that NDIs made using Ti-15Zr can successfully withstand intraoral loading. Therefore, this study aimed to perform a thorough failure analysis of two fractured NDIs after medium-term in vivo use. The null hypothesis set is that fatigue mechanism is implicated in the intraoral fracture of retrieved NDI.

2. Materials and methods

2.1. Sample collection

The study was initiated after securing an approval from the internal review board and obtaining informed patient consent. Two fractured NDI fixtures (Roxolid®, SLActive implants, Straumann, Basel, Switzerland) were retrieved from two different locations in the same patient at two different times. A 68-years-old woman was treated and rehabilitated with a mandibular screw-retained-implant-supported full-arch prosthesis and a maxillary screw-retained-implant-supported prosthesis to replace the missing maxillary posterior teeth (Fig. 1). Missing maxillary right posterior teeth were replaced by two implants, and the maxillary left posterior teeth were replaced by only one implant. All implants had SLA surfaces (Straumann Implants System, Straumann, Basel, Switzerland). On the upper-right side, two implants were placed in the area corresponding to #16 and #15. A splinted screw-retained PFM fixed prosthesis with a mesial cantilever pontic was used to replace the missing #16, #15, and #14. On the upper left side, a single

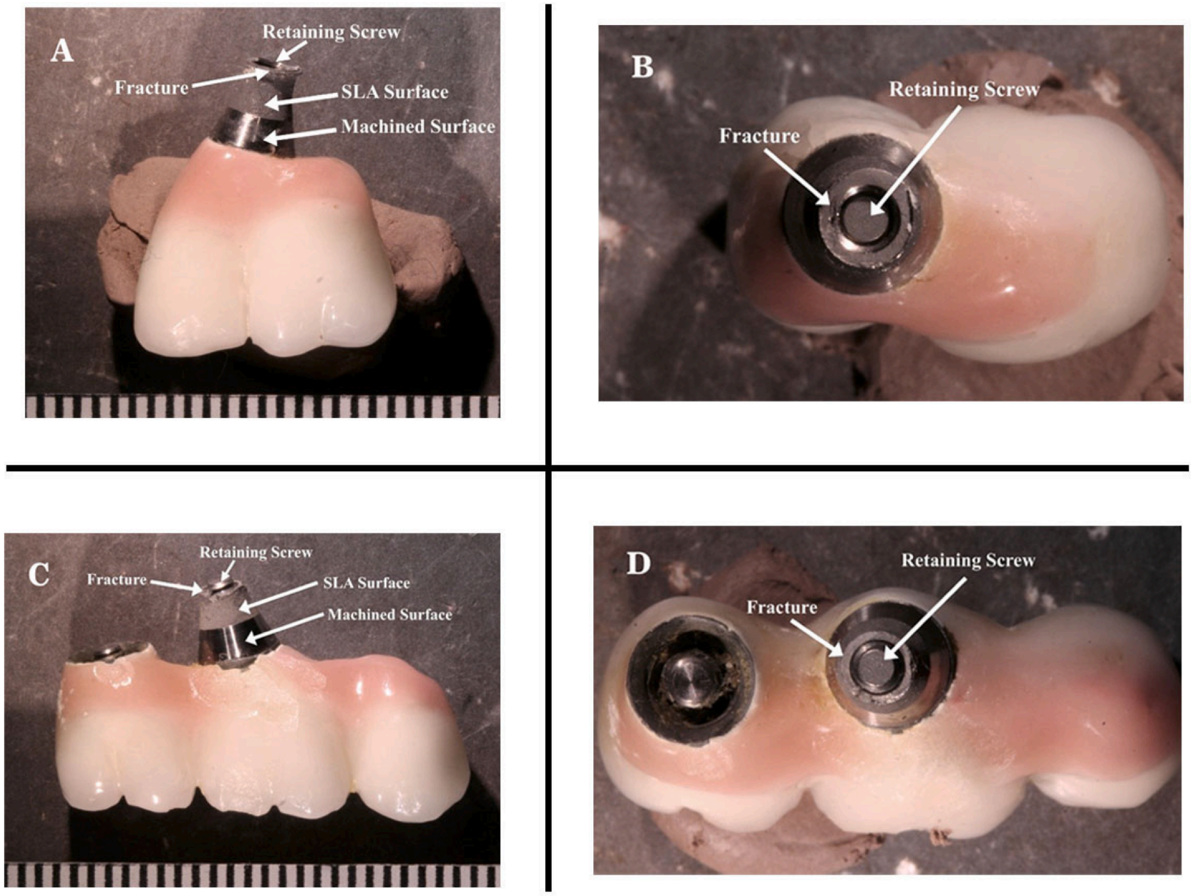

Fig. 2. A and B are macroscopic views of narrow dental implants (NDI)-specimen-1. (a) Side view showing the location of the fracture in the implant fixture and the SLA surface on it. (b) Top view showing the fracture surface on the implant fixture. (c) and (d) are macroscopic views of narrow dental implant (NDI)-specimen-2. (a) Side view showing the location of the fracture in the implant and the SLA surface on it. (b) Top view showing the fracture surface on the implant fixture.

implant was placed in the area of #24, and a screw-retained PFM fixed prosthesis with a distal cantilever pontic was used to replace missing #24 and #25. The implant in the area of #24 fractured first after 12 months in service, and that the area of #15 fractured thereafter after 17 months in service. The retrieved top parts of the two fractured ND Roxolid® implant fixtures, which were attached to the prosthetic components, were ultrasonically cleaned and stored in plastic vials containing methanol before being subjected to thorough failure analysis. In this study, the first retrieved fractured Roxolid® implant (in service for 12 months) was designated as NDI-specimen-1 (Fig. 2A & B), and the second retrieved fractured Roxolid® implant (in service for 17 months) was designated as NDI-specimen-2 (Fig. 2C &D).

2.2. Macroscopic examination

Macroscopic examination and photography were performed using a Canon Rebel XT digital camera with a Canon EF-S 60 mm Macro Lens. A higher-magnification examination of the fractures on both retrieved fractured parts of the NDI fixtures was performed using a Keyence Model VHX-1000 digital microscope (Keyence Corporation of America, Itasca, IL, USA). Scanning electron microscopy (SEM) of the fracture surfaces was performed using a JEOL JSM 6510LV (JEOL USA, Inc., Peabody, MA, USA) SEM operated at 20 kV with secondary electron imaging (SEI). Prior to the examination, the specimens were ultrasonically cleaned in methanol for 10 min. Additionally, the SLA surface of theNDI-specimen-2, as shown in Fig. 3a, was examined and analyzed by SEM under the aforementioned operating conditions.

2.3 Light and SEM/EDX analysis

NDI-specimen-1 was selected for destructive testing. The specimen was first sectioned, to obtain a cross section through the implant. The resulting specimen was then mounted in LECO Long Cure Epoxy (LECO Corporation, St. Joseph, MI,) to observe the cross-section labeled first cut. This specimen was then ground through 600 grit Silicon carbide paper, polished with 1.0 μm aluminum oxide and etched with Kroll's reagent (85% water, 10% nitric acid, and 5% hydrofluoric acid) for 5 s by immersion. The specimen was then examined with an Olympus PME3 metallographic microscope (Olympus Corporation of the Americas, Center Valley, PA, USA) using bright-field illumination and a JEOL JSM 6510LV SEM operated at 20 kV with secondary electron imaging. An energy dispersive X-ray spectrum was obtained from an as-polished area on the implant cross-section at 500× nominal magnification using a JEOL JSM 6510LV scanning electron microscope with a Thermo Fisher NORAN System 7 X-ray analysis system (Thermo Fischer Scientific, Madison, WI, USA). The spectrum was obtained at 20 kV, 15 mm working distance, and 60 spot size using a live-time acquisition of 100 s. The spectrum was quantified using standardless semiquantitative analysis with phi-rho-z correction.

2.4. Vickers microhardness testing

The Vickers microhardness of the implant material was determined using a Buehler Micromet 5101 (Buehler Ltd., Lake Bluff, IL) microhardness tester with a 500 g load and 15 s application time. The testing machine was checked using a Buehler test block (Serial #59-0366) and found to be accurate within 2% at a hardness of approximately HV700.

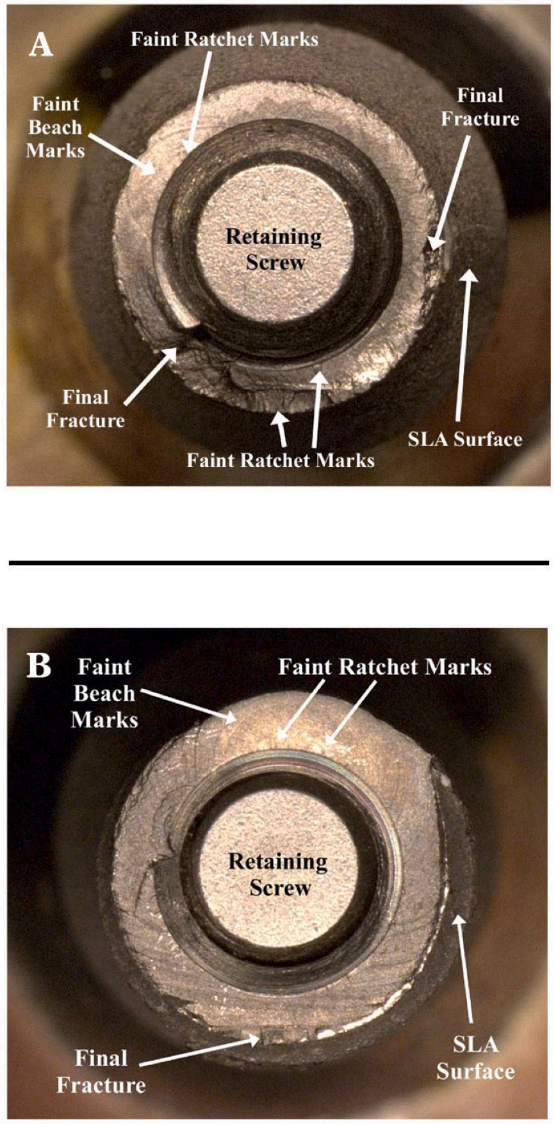

Fig. 3. Macroscopic views of the fracture surfaces of (a) narrow dental implant (NDI)-Specimen-2 and (**b**) NDI-Specimen-1. In both specimens, faint ratchet marks indicate the regions at which fatigue cracking initiated.

Four hardness readings were recorded around the circumference of each sample.

3. Results

3.1. Macroscopic examination

As seen in Fig. 2, low-magnification macroscopic examination revealed that the fracture in both retrieved specimens occurred near the end of the retaining screw inside the implant and followed the root of the internal thread (crest of the retaining screw). The fracture surfaces were approximately perpendicular to the axis of the implant and exhibited little observable plastic deformation. The dull gray areas on the sides of the implants were parts that had received SLA surface treatment.

Fig. 3 presents higher magnification macroscopic views of the fractures of both retrieved specimens. As can be seen from the faint ratchet and beach marks on the fracture surface of NDI-specimen-2 in Fig. 3a, fatigue cracks initiated at the internal thread surface in the upper left quadrant, lower internal thread, and the lower outside surface. These cracks, especially the one in the upper left quadrant propagated around the implant until final fracture. Fig. 3b revealed faint beach and ratchet marks on the fracture surface of NDI-specimen-1. As can be seen, fatigue cracking initiated at the internal thread surface in the upper part of the fracture and then propagated downward until final fracture.

3.2. Light and SEM/EDX analysis

Microscopic examinations using SEM are shown in Figs. 4 and 5. As can be seen from the ratchet and beach marks in Fig. 4A and B, a fatigue crack started at the internal thread root in the implant in the upper part of the fracture, and then propagated upward and around the implant until the final fracture at the bottom. Fig. 4c shows the presence of fatigue striations in the small grains of the implant alloy. As can be seen from the ratchet and beach marks in Fig. 5A–C, fatigue fracture initiated at the internal thread surface in the upper left quadrant of the fracture and at the internal thread surface and the outer SLA surface in the lower part of the fracture. Fig. 5D shows the presence of fatigue striations in the small grains of the implant alloy. As shown in Fig. 6A, a light micrograph of a cross-section of the implant alloy exhibits a fine grain structure. The higher-magnification SEM micrograph in Fig. 6B shows

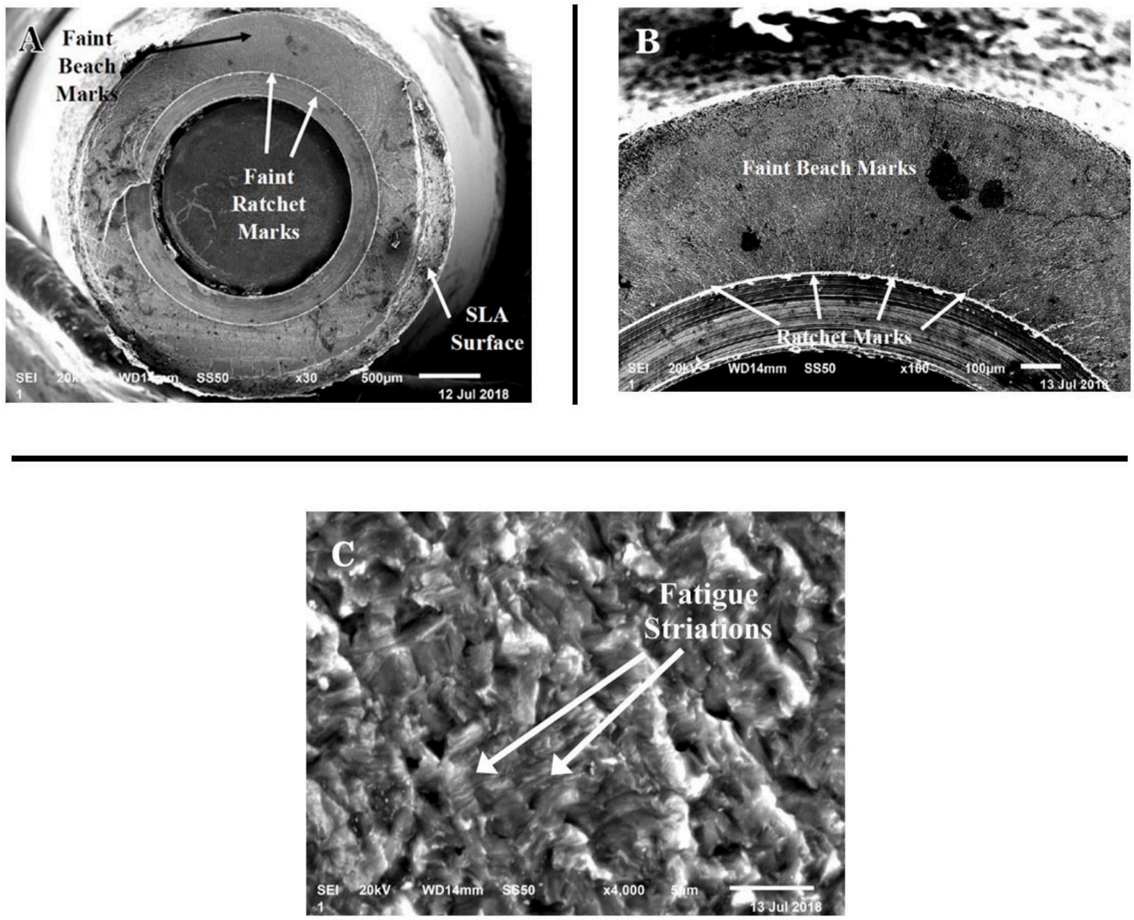

Fig. 4. SEM micrographs of fracture features on the fracture surface of NDI-specimen-1. (a) Low magnification view showing faint beach and ratchet marks in the upper part of the fracture. (b) Higher magnification view of the upper part showing faint ratchet marks and beach marks indicating that fatigue cracking started at the root of a thread in the implant and propagated outward. (c) High magnification view of fracture in the upper part showing fatigue striations in the very fine grains of the implant alloy.

that this grain structure consists of a uniform distribution of irregularly shaped grains with diameters ranging from approximately 2 to 5 µm. As seen in the spectrum in Fig. 6C, the alloy consists mostly of Ti and Zr with traces of Al and Si. A standardless semiquantitative analysis of the spectrum with phi-rho-z corrections showed that the alloy consists of (% wt) Ti: 85.86, Zr: 13.83, Al:0.28 and Si:0.03.

3.3. Vickers microhardness testing

The overall microhardness value of the implant alloy was found to be HV288 ± 5.

4. Discussion

According to the results of this study the null hypothesis shall be accepted. To the best of our knowledge, a thorough failure analysis of retrieved NDI fixtures has not been reported. However, fatigue failure and fracture analysis of prosthetic retaining screws for implant-supported and retained prostheses have been previously reported in the literature (Al Jabbari et al., 2008). Al Jabbari et al. documented the classical three stages of fatigue failure in prosthetic retaining screws that failed in patients after long-term service. Their findings were comparable to the observations in this study regarding the presence of ratchet and beach marks and striations. The only difference were the features of fatigue failure in this study; beach marks were fainter and striations smaller in size. This is mainly due to the difference in the alloy type. In this study, the alloy was found to be Ti-14Zr, whereas in a previous study, the alloys of the prosthetic retaining screws were mainly 70% wt gold alloys. Gold-based alloys are more ductile with larger grain size, allowing for more distinct macro/microscopic fatigue fracture features. In this study, striations (Fig. 6d) were difficult to observe because of the small grain size (2–5 µm) of the Roxolid® alloy.

In this study, both metallography and energy-dispersive spectroscopy showed that the alloy was Roxolid®. Fig. 6 shows that this alloy is extremely fine-grained, with the grain diameters of the irregularly shaped grains being in the range of 2–5 µm. This is in total agreement with the microstructure of Roxolid® reported in two previous studies (Bernhard et al., 2009, Medvedev et al., 2016). The results of EDS analysis shown that the alloy had a composition of Ti-15 wt% Zr, which is the composition of the Roxolid® alloy. In the current study, microhardness measurements showed that the implant had a Vickers hardness of HV288, which was slightly higher than that reported previously (HV250) by Correa et al. (2014).

In the current study, the authors further examined and characterized the outer SLA surface on NDI-specimen-2 by SEM, as shown in Fig. 2A. As shown in Fig. 6D, the outer surface of the implant fixture exhibited a bimodal distribution of coarse and fine features. These features are similar to those reported for Roxolid® by Bernhard et al. (2009) and Medvedev et al. (2016). As described by Medvedev et al. (2016), SLA treatment involves sand blasting with corundum, followed by acid etching with a solution of sulphuric and hydrochloric acid.

In this study, NDI-specimen-1 failed first after 12 months of in-service, whereas NDI-specimen-2 failed after 17 months. This difference may be because NDI-specimen-2 was splinted to another distal

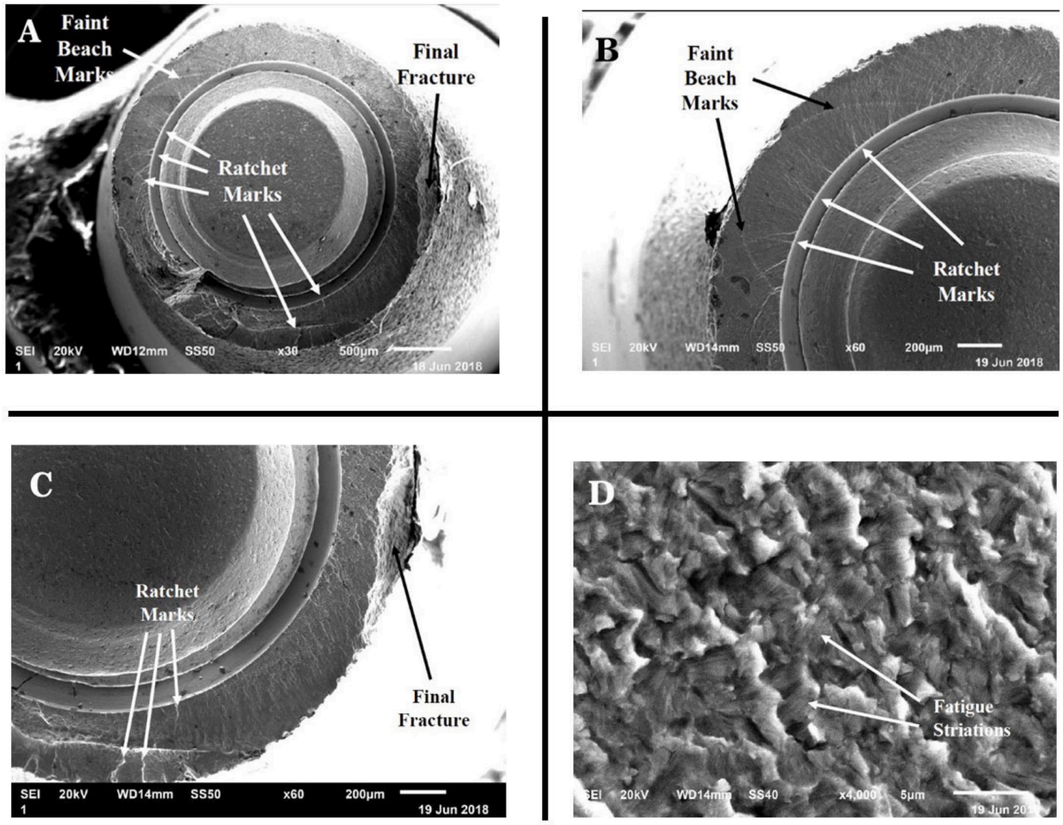

Fig. 5. Scanning electron micrograph (SEM) of fracture features on the fracture surface of narrow dental implant (NDI)-specimen-2. (a) Low magnification view showing faint ratchet marks and beach marks in the upper left quadrant of the fracture. (b) Higher magnification view of the upper left quadrant showing ratchet marks and beach marks indicating that fatigue cracking started at the root of a thread in the implant and propagated outward. (c) Higher magnification view of lower right quadrant showing ratchet marks indicting the origin of additional fatigue cracking. (d) High magnification view of fracture in the upper left quadrant showing fatigue striations in the fine grains of the implant alloy.

implant and was not supported by a cantilever pontic alone, which possibly increased the in-service time in the patient's mouth. However, in both scenarios, a pontic cantilever connected to a crown supported and retained by an NDI in the posterior regions may not be advisable as it may lead to an NDI fixture fracture within the first 18 months of being in-service. In addition, this study suggests that the treating prosthodontists preferably limits the size of the occlusal table of a crown, retained and supported by an NDI in the posterior area, to minimize off-axis loading, which may initiate fatigue cracks and fractures.

Although the results of this study can not be generalized due to limited number of retrieved NDIs, the observations and treatment recommendations of this study are valuable and important for consideration, providing that a previous study reported favorable tensile and fatigue behavior of Straumann's Roxolid® (Ti-15 wt% Zr) alloy (Bernhard et al., 2009). Bernhard et al. (2009) reported a tensile strength of 953 MPa of the alloy, which was 40% greater than that of cp-Ti. They also reported that the endurance levels for the Roxolid® was 13 to 42% greater than that for cold worked cp-Ti implants. Despite their improved mechanical properties, NDIs fail by a mechanical degradation mechanism of the fatigue mechanism, implying that they are not free of mechanical degradation phenomena during intra-oral off-axis loading. Therefore, further controlled studies with larger samples number and further laboratory testing are required to provide best guidelines for safer and more successful applications of NDI fixtures in posterior regions.

5. Conclusions

Within the limitations of this retrieval analysis study, the following conclusions can be drawn:

1. The fracture of a single NDI supporting and retaining a cantilever fixed prosthesis in the posterior region observed in this study shows that the fracture and failure of NDI fixtures occur mainly due to fatigue.
2. Fatigue cracks can be initiated and grow in NDI fixtures supporting and retaining the cantilever of a fixed prosthesis, leading to catastrophic fracture even before the patient and/or clinician determines the presence of any complication.

Ethical approval and consent to participate

All methods were carried out in accordance with relevant guidelines and regulations. The study was initiated after securing Internal Review Board (IRB) and obtaining informed patient consent.

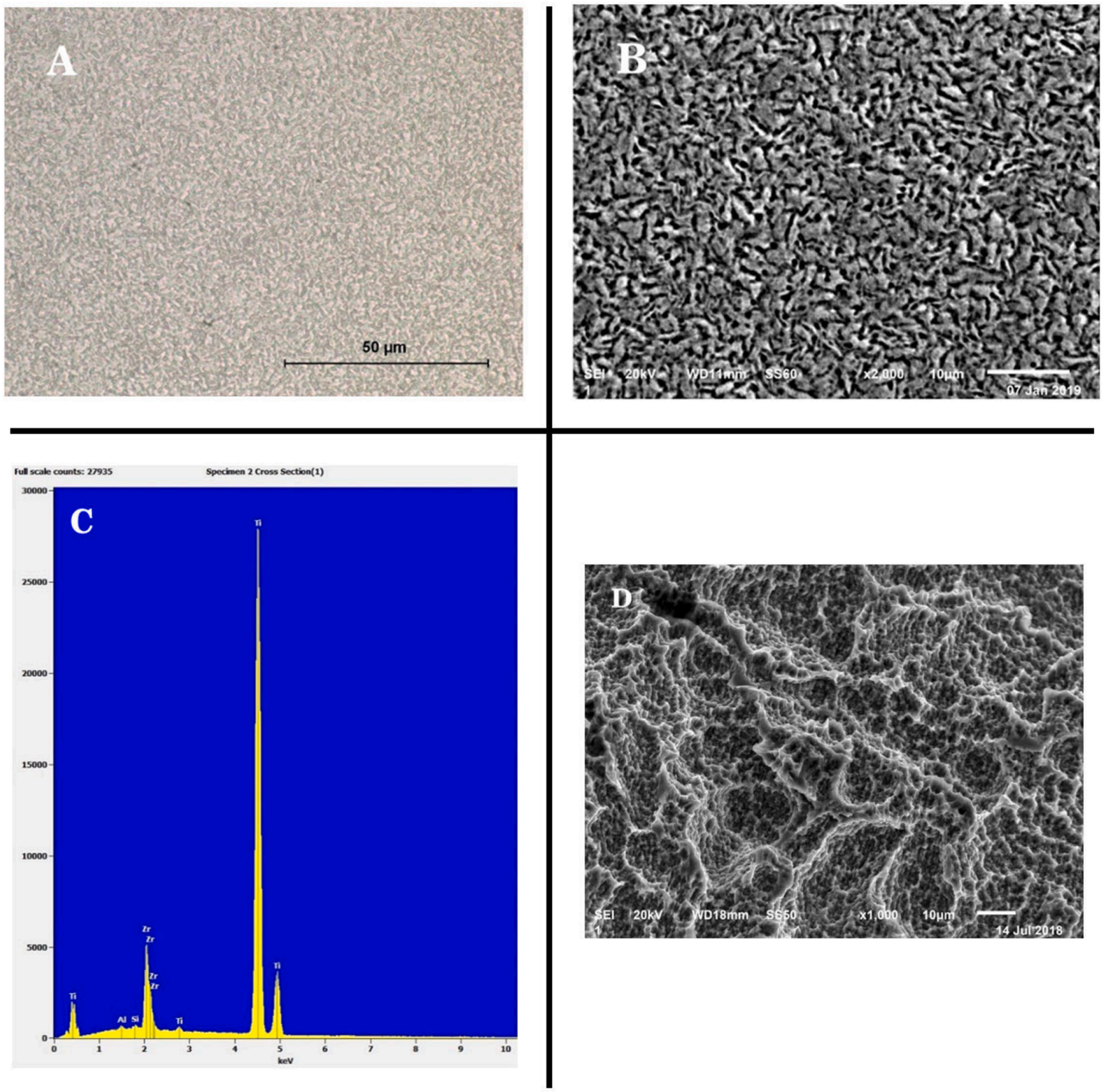

Fig. 6. (a) Light micrograph of implant cross section showing the fine grain structure. (b) Scanning electron micrograph (SEM) of the implant cross section shown in (a) showing a uniform distribution of small irregularly shaped grains in the range of 2 to 5 µm in size. (c) Energy dispersive X-ray spectroscopy (EDS) spectrum from the as-polished surface of the implant cross section showing that the alloy consists mostly of Ti and Zr with small amounts of Al and Si. (d) SLA surface on narrow dental implant (NDI)-specimen-2 showing the bimodal distribution of surface features produced by sand blasting with corundum and acid etching.

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