Scanning Electron Microscopy Observations of Failures of Implant Overdenture Bars: A Case Series Report

J. Neil Waddell, MDipTech(Dent Tech), PGDipCDTech, HDE;*
Alan GT Payne, BDS, MDent, DDSc, FCD(SA);† Michael V. Swain, BSc, PhD;‡
Jules A. Kieser, BDS, PhD, DSc, FLS, FDSRCSEd§

ABSTRACT

Background: Soldered or cast bars are used as a standard of care in attachment systems supporting maxillary and mandibular implant overdentures. When failures of these bars occur, currently there is a lack of evidence in relation to their specific etiology, location, or nature.

Purpose: To investigate the failure process of a case series of six failed soldered bars, four intact soldered bars, and one intact cast milled bar, which had been supporting implant overdentures.

Materials and Methods: A total of 11 different overdenture bars were removed from patients with different configuration of opposing arches. A failed bar (FB) group ($n = 6$) had failed soldered overdenture bars, which were recovered from patients following up to 2 years of wear before requiring prosthodontic maintenance and repair. An intact bar (IB) group ($n = 5$) had both soldered bars and a single cast milled bar, which had been worn by patients for 2 to 5 years prior to receiving other aspects of prosthodontic maintenance. All bars were examined using scanning electron microscopy to establish the possible mode of failure (FB) or to identify evidence of potential failure in the future (IB).

Results: Evidence of a progressive failure mode of corrosion fatigue and creep were observed on all the FB and IB usually around the solder areas and nonoxidizing gold cylinder. Fatigue and creep were also observed in all the IB. Where the level of corrosion was substantial, there was no evidence of wear from the matrices of the attachment system. Evidence of an instantaneous failure mode, ductile and brittle overload, was observed on the fracture surfaces of all the FB, within the solder and the nonoxidizing gold cylinders, at the solder/cylinder interface.

Conclusion: Corrosion, followed by corrosion fatigue, appears to be a key factor in the onset of the failure process for overdenture bars in this case series of both maxillary and mandibular overdentures. Limited sample size and lack of standardization identify trends only but prevent broad interpretation of the findings.

KEY WORDS: bar, corrosion, creep, failure, fatigue, overdenture, overload

INTRODUCTION

The standard of care for removable overdentures in the edentulous maxilla ranges from as few as four implants to as many as eight implants, connected with different types of bars. The bars can be soldered[1–3], cast with milled designs[4–7], made using spark erosion[8] or even

*Senior Lecturer, Dental Technician, PhD student, Oral Implantology Research Group, Sir John Walsh Research Institute, School of Dentistry, University of Otago, Dunedin, New Zealand; †Associate Professor of Prosthodontics, Oral Implantology Research Group, Sir John Walsh Research Institute, School of Dentistry, University of Otago, Dunedin, New Zealand; ‡Professor of Biomaterials, Oral Implantology Research Group, Sir John Walsh Research Institute, School of Dentistry, University of Otago, Dunedin, New Zealand; §Professor and Chair of Oral Biology, Oral Implantology Research Group, Sir John Walsh Research Institute, School of Dentistry, University of Otago, Dunedin, New Zealand

Reprint requests: Associate Professor, Alan GT Payne, Oral Implantology Research Group, Sir John Walsh Research Institute, School of Dentistry, 280 Great King Street, Dunedin, New Zealand; e-mail: alan.payne@dent.otago.ac.nz

This research was presented at the 45th Annual Meeting of the Australian/New Zealand Division of the International Association for Dental Research, September 25–28, 2005, in Queenstown, New Zealand.

DOI 10.1111/j.1708-8208.2008.00127.x

milled precision bars using nonprecious alloy (cobalt-chromium).[9] Controversy, however, still hinges on the number of implants, as well as on the specific type of connecting bars,[10–13] with or without cantilever extensions.[2,14]

For soldered type IV gold alloy bars, nonoxidizing gold alloy cylinders are placed onto the abutments or implants and connected by soldering using soldering or brazing materials.[15,16] For cast or milled bars, a burnout pattern of the complete bar attachment system that has been fabricated to incorporate the cast-on nonoxidizing gold cylinder is invested. This is then cast in a type IV gold alloy as a one-piece casting. This is either trimmed or milled to receive the other components of the attachment system that is incorporated into the intaglio surface of the overdenture.[4] The fracture or failure of overdenture bars (the patrices) in the interconnected sections themselves occurs far less frequently than that of the matrices in the intaglio surface of the overdentures.[14,17] Previous review of the literature has concluded that the authors do not comment on the nature, site, or etiology of failure.[18]

Goodacre and colleagues[17] reviewed the literature and reported that there were essentially six hypothesized causes for metal framework fractures, including overdenture bars. These were inadequate metal thickness, poor solder joints, excessive cantilever length, alloys with inadequate strength, patients' parafunctional habits, and improper framework design. Some of these specifically relate to overdenture bars, as opposed to frameworks for fixed implant bridges. As a result, there is a need for more reports on both the laboratory-based and clinical factors that could be related to the etiology of soldered or cast bar fractures or failure. Evidence with an evaluation of simple laboratory failure modes for distal cantilevers has shown that in soldered joints used for overdenture bars, cracking is initiated in the solder due to fatigue. This is regardless of the type of soldering material. The joints have relatively low yield stresses and are prone to plastic deformation under maximum occlusal forces.[15]

From a biomaterials aspect, the hypothesized causes for the fracture of overdenture bars can be related to a long tradition of engineering analysis of biomechanics of failure in welded and soldered joints. These use optical and scanning electron fractography to analyze crack initiation and propagation of failed structures that have been subjected to cyclic multiaxial loading.[19–23] This methodology has, to date, had limited application to similar situations in dentistry.[15,24–27] An established method of the determination and classification of metallic fracture lists two modes of failure; progressive failure (subdivided into fatigue, corrosion, wear, and creep), and instantaneous failure (subdivided into ductile overload and brittle overload).[23] This approach enables the identification of the cause, nature, and location of the failure, which in turn leads to a more valid solution and avoidance of the problem in the future. This raises the question of the inevitable relationship between the application of engineering fatigue crack analysis in the failure of overdenture bars. As a result, there is a need to consider engineering methods and scanning electron microscopy (SEM) to assess the causes of possible mode of failure or to identify evidence of potential failure in the future of overdenture bars.

The aim of this study was to investigate the failure process using SEM analyses of six failed soldered bars, four intact soldered bars, and one intact cast milled bar removed from patients who had been wearing either maxillary or mandibular implant overdentures for up to 5 years.

MATERIALS AND METHODS

Patient Sample

These were selected with inclusion criteria being that they were failed or intact overdenture bars connected to two to five implants removed from patients with one or both edentulous jaws (males and females aged 55–80 years) (between June 2002 and June 2007) for either prosthodontic repair or routine clinical research measurements. The overdenture bars examined were to have been in clinical function supporting either mandibular or maxillary overdentures as part of bar attachment systems for a period of at least 1 year. Exclusion criteria were related to the components being any other type of implant overdenture attachment system. Local ethical approval from the Lower South Island Ethics Committee, New Zealand had been obtained previously for any patients in ongoing randomized controlled clinical trials.

Overdenture Bars

A total of 11 overdenture bars removed for SEM observations were from

1. seven participants included in randomized controlled clinical trials on implant overdentures in the Clinical Overdenture Research Project, Oral

Implantology Research Group, Sir John Walsh Research Institute, School of Dentistry, University of Otago, Dunedin, New Zealand. These were bars supporting maxillary three-implant overdentures, opposing mandibular two-implant overdentures.

2. four routine patients seeing graduate prosthodontic students in the Discipline of Prosthodontics, Department of Oral Rehabilitation, School of Dentistry, University of Otago, Dunedin, New Zealand for routine prosthodontic maintenance treatment. Informed consent was obtained in standard manner for these patients. These comprised of
   a. two patients with conventional complete maxillary dentures opposing mandibular bar overdentures on two or three implants with distal cantilever extensions. All bars that had distal cantilevers were of 10 mm length from the center of the distal gold cylinder.[14]
   b. two patients with maxillary bar overdentures on four or five implants with an opposing mandibular dentition.

The total 11 overdenture bars were divided into two groups:

1. those with failed bars (FB group: $n = 6$):

These totaled six failed overdenture bars from four maxillary overdentures and two mandibular overdentures worn by patients for up to 2 years prior to failure requiring prosthodontic maintenance and repair (Table 1). The bars were either
   a. micro-U-shaped bars without distal extensions with corresponding matrices (old code DCA512; Nobel Biocare AB, Göteborg, Sweden) or
   b. mini-egg-shaped Dolder bars with and without distal extensions with corresponding matrices (048.411; 048.413 Institut Straumann AG, Basel, Switzerland)

The bars were connecting implants at implant level; or to either standard abutments (Southern Implants Ltd. South Africa) or multi-unit abutments (Nobel Biocare AB, Göteborg, Sweden) were used with corresponding gold cylinders. Typical clinical observations prior to the removal of the FB are shown in Figure 1. All the FB had been manufactured using soldered joints where type IV gold alloy bars were soldered to nonoxidizing gold cylinders using a gold solder (Degunorm-Lot 700, Degudent, Germany) and a liquefied petroleum gas/oxygen flame soldering technique.

2. and those with intact bars (IB group: $n = 5$)

TABLE 1 Description of Failed Bar Group

	Type of Bar Overdenture	Time to Failure (years)	Opposing Arch
Failure 1	Mandibular implant overdenture on two implants with bilateral distal extension cantilevers. Failure occurred through the joint of one of the cantilever extensions.	1	Complete maxillary denture
Failure 2	Maxillary overdenture on 3 implants. Failure occurred at the middle abutment of a connected bar between the 3 implants.	1	Mandibular two-implant overdenture
Failure 3	Maxillary overdenture on 4 implants. Two separate bilateral bars, failure occurred on left side anterior abutment.	1	Mandibular five-implant fixed bridge
Failure 4	Maxillary implant overdenture on three implants. Failure occurred at distal abutment on the one side	2	Mandibular two-implant overdenture
Failure 5	Maxillary implant overdenture on three implants. Failure occurred at the middle abutment of a connected bar between the three implants.	2	Mandibular two-implant overdenture
Failure 6	Mandibular implant overdenture on three implants with bilateral distal extension cantilevers. Failure occurred through the solder joint and cylinder of the cantilever extension.	2	Complete maxillary denture

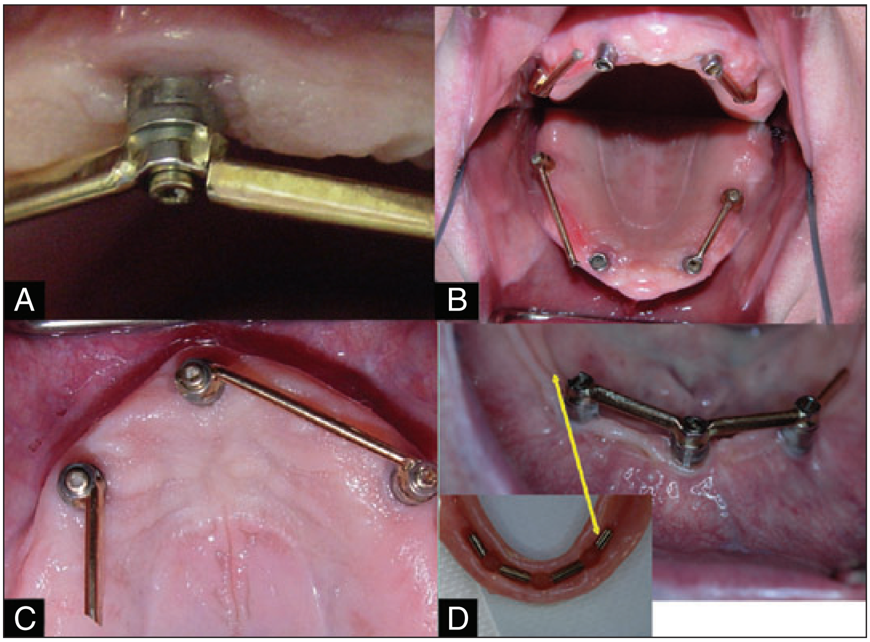

Figure 1 Clinical presentation of some patients of failed bar group. *A*, Failure occurred after 12 months; *B*, 24 months; *C*, 12 months. *D*, Fractured distal cantilever extension. Failure occurred after 24 months.

A further four intact maxillary soldered bars and one cast type IV gold milled bar worn for 2 to 5 years prior to receiving other aspects of prosthodontic maintenance were examined (Table 2).

The bars were

a. micro-U-shaped bars without distal extensions with corresponding matrices (old code DCA512) connecting implants at implant level; or to either standard abutments or multi-unit abutments were used with corresponding gold cylinders.
b. The single gold milled bar had been connecting standard abutments and gold cylinders (Nobel Biocare AB, Göteborg, Sweden) and accommodating a hybrid design, including precision attachments as part of the attachment system.

Examples of their clinical presentation are shown in Figure 2. All the intact soldered bars had been manufactured using the same method as the FB; however, the type IV gold milled bar had been made as a one-piece casting incorporating cast-on nonoxidizing gold cylinders for attachment to the implant abutments.

SEM

Examination of each of the overdenture bars in both groups was done under the scanning electron microscope (SEM, Cambridge Instruments S360, Cambridge Instruments, Cambridge, UK). For the FB group, we identified the sites of failure and used an established method to describe the etiology of failure.[23] We also subjected the five IB in the IB group to SEM analysis, using the same method to identify any signs of surface evidence of their impending failure in the future.

TABLE 2 Description of Intact Bar Group

Specimen Number	Type of Bar Overdenture	Time to Examination (years)	Opposing Arch
Intact bar 1	Maxillary implant overdenture on three implants.	2	Mandibular two-implant overdenture
Intact bar 2	Maxillary implant overdenture on three implants.	2	Mandibular two-implant overdenture
Intact bar 3	Maxillary implant overdenture on three implants.	2	Mandibular two-implant overdenture
Intact bar 4	Maxillary implant overdenture on three implants.	5	Mandibular two-implant overdenture
Intact bar 5	Maxillary implant overdenture on five implants.	5	Mandibular dentition

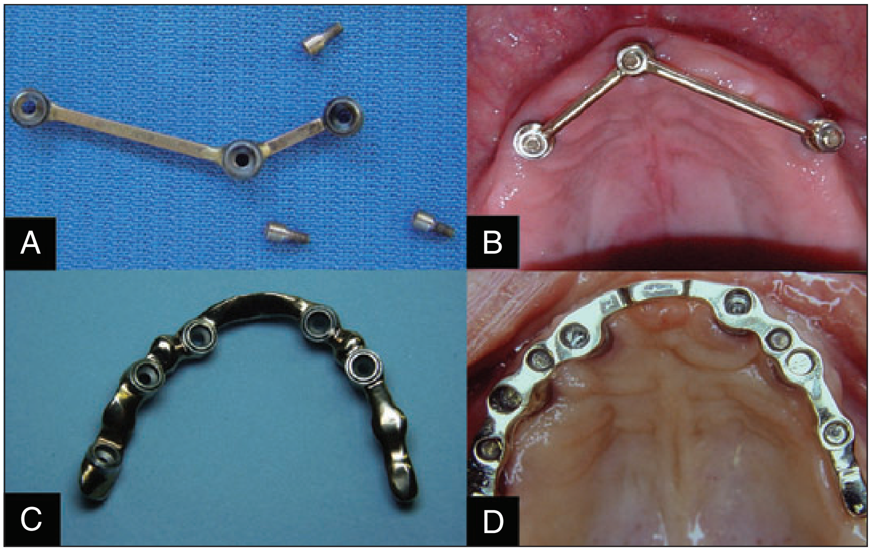

Figure 2 Clinical presentation of some patients of intact bar group. *A,* Shows underside of maxillary overdenture bar attachment system using U-shaped gold bars soldered to nonoxidizing gold cylinders; *B,* Intraoral view; *C,* Shows underside of maxillary overdenture bar attachment system using cast milled gold bars incorporating cast-on nonoxidizing gold cylinders; and *D,* Intra-oral view.

RESULTS

The SEM observations were classified into two modes of failure[23]: progressive failure subdivided into fatigue,[28] corrosion,[29] wear, and creep, and instantaneous failure subdivided into ductile overload and brittle overload (Table 3).[30,31] Generally, in the FB group, the location of the bar fractures occurred through the solder to the nonoxidizing gold cylinders in all six failures. In addition, there was fracture partly through the gold cylinders at the solder-cylinder interface in five of the six failures. The progressive mode of failure (subdivided into corrosion, fatigue, and creep) was observed in all the failures, except for one where damage prevented its observation. The instantaneous mode of failure (subdivided into ductile and brittle overload) occurred in all the failures except in one where damage also prevented its observation. However, in the IB group, various stages of a progressive mode of failure, corrosion, fatigue, and creep were also observed in all the overdenture bars. Several of the nonoxidizing gold cylinders, on both the FB and IB showed evidence of crevice corrosion on the fitting edge where the cylinder made contact with the abutment or implant head. In one instance, the degree of internal crevice corrosion inside the cylinder was extensive. Wear of the bars (damage from insertion of the denture by the matrices or wear on the bars from the matrices during cyclic loading from mastication), as distinct from minor scratch marks, was not observed on any of the FB or IB.

FB Group

For failure 1, corrosion was observed through the solder on the superior and lateral sides, with evidence of porosity defects in the solder. In the lower half of the overdenture bar, a smooth fracture at the solder-cylinder interface had occurred (Figure 3A). The point of initiation appeared to be from the defects (porosity) in the solder (see Figure 3B). Across the top third of the failure surface, the area in tension and torque, there was evidence of cleavage type cracks with branching in different directions. There was also evidence of grain distortion that indicates a ductile overload (see Figure 3C), and of buckling and creep on the underside of the solder joint in the zone of compression (see Figure 3D). There was evidence of brittle overload shown by the intergranular fracture that had taken place within the surface layer of the cylinder (cylinder/cylinder break) across the lower third of the cylinder where the solder had been jointed to the cylinder. No distortion was evident (see Figure 3E).

For failure 2, corrosion was observed on the superior and lateral sides of the solder and also on the surfaces of the nonoxidizing cylinder in the areas adjacent to where the solder had flowed onto the cylinder. There was no corrosion on the two distal abutments. There was no evidence of creep deformation on the underside of the solder joint. Between areas of damage caused by rubbing, evidence of intergranular fracture, which had

TABLE 3 Summary of Modes of Failure

	Location of Failure/Fracture	Progressive Failure Mode Observations				Instantaneous Failure Mode Observations	
		Corrosion	Fatigue	Wear	Creep	Ductile Overload	Brittle Overload
Failure 1	Failure through solder joint and abutment gold cylinder.	Yes	Yes	No	Yes	Yes	Yes
Failure 2	Failure through solder joint.	Yes	Unknown due to surface damage	No	No	Unknown due to surface damage	Yes
Failure 3	Failure through solder joint and abutment gold cylinder.	Yes	Yes	No	Yes	Yes	Yes
Failure 4	Failure through solder joint and abutment gold cylinder.	Yes	Yes	No	Yes	Yes	Yes
Failure 5	Failure through solder joint and abutment gold cylinder.	Yes	Yes	No	Yes	Yes	Yes
Failure 6	Failure through solder joint and abutment gold cylinder.	Yes	Yes	No	Yes	Yes	Yes
	Location of Progressive Failure Mode	Corrosion	Fatigue	Wear	Creep		
Intact bar 1	Solder joint and abutment gold cylinder.	Yes	Yes	No	Yes		
Intact bar 2	Solder joint and abutment gold cylinder.	Yes	Yes	No	Yes		
Intact bar 3	Solder joint and abutment gold cylinder.	Yes	Yes	No	Yes		
Intact bar 4	Cast gold bar around implant abutments.	Yes	Yes	No	Yes		
Intact bar 5	Solder joint and abutment gold cylinder.	Yes	Yes	No	Yes		

taken place within the solder (solder/solder break), was identified.

For failure 3, the center third of the joint, extending from below the top area of the joint down to the base, was devoid of solder, having large porosity defects, and even showed the bur marks from the manufacturing phase on the cylinder surface and shiny gold colored solder on the adjacent surface (Figure 4, A and B). Fatigue striations were present on the solder in the left top quarter of the joint, and buckling-induced deformation was present at the base of the solder in the zone of compression. There was intergranular brittle fracture extending within the cylinder where the crack has moved from the solder into the cylinder (see Figure 4C). Corrosion was observed on the superior and lateral sides of the solder and on the top and side surfaces of the nonoxidizing gold cylinder (see Figure 4D).

For failure 4, corrosion was also present on the lateral and superior sides of the solder and on the lower portion of the cylinder. Early stages of corrosion and cracking were detected at the opposite ends of the bar in the solder and nonoxidizing gold cylinder. The central area of the fracture occurred through the cylinder, with evidence of a brittle gray-colored intergranular fracture within the cylinder at the solder-cylinder interface (Figure 5, A and B). There were corrosion fatigue and transgranular fatigue striations on the top third of the solder, near the top of the cylinder. The middle area of the solder break surface showed cleavage type cracks, with branching in different directions (see Figure 5C). The lower portion of the solder shows evidence of buckling, as well as cracking, where it joined the gold cylinder (see Figure 5D).

For failure 5, corrosion was present on the lateral and superior sides of the solder. There were corrosion fatigue and transgranular fatigue striations on the first third of the labial side of the break surface, with buckling on the opposite palatal side on the solder surface. The middle area showed evidence of cleavage type cracks, with branching in different directions. The palatal third showed brittle intergranular fracture within the cylinder at the solder-cylinder interface.

For failure 6, in addition to the usual corrosion and porosity defects, transgranular fatigue striations (Figure 6, A and B) were observed on the right-hand side of the fracture surfaces, which may indicate the initial zone of failure. The crack plane passed through

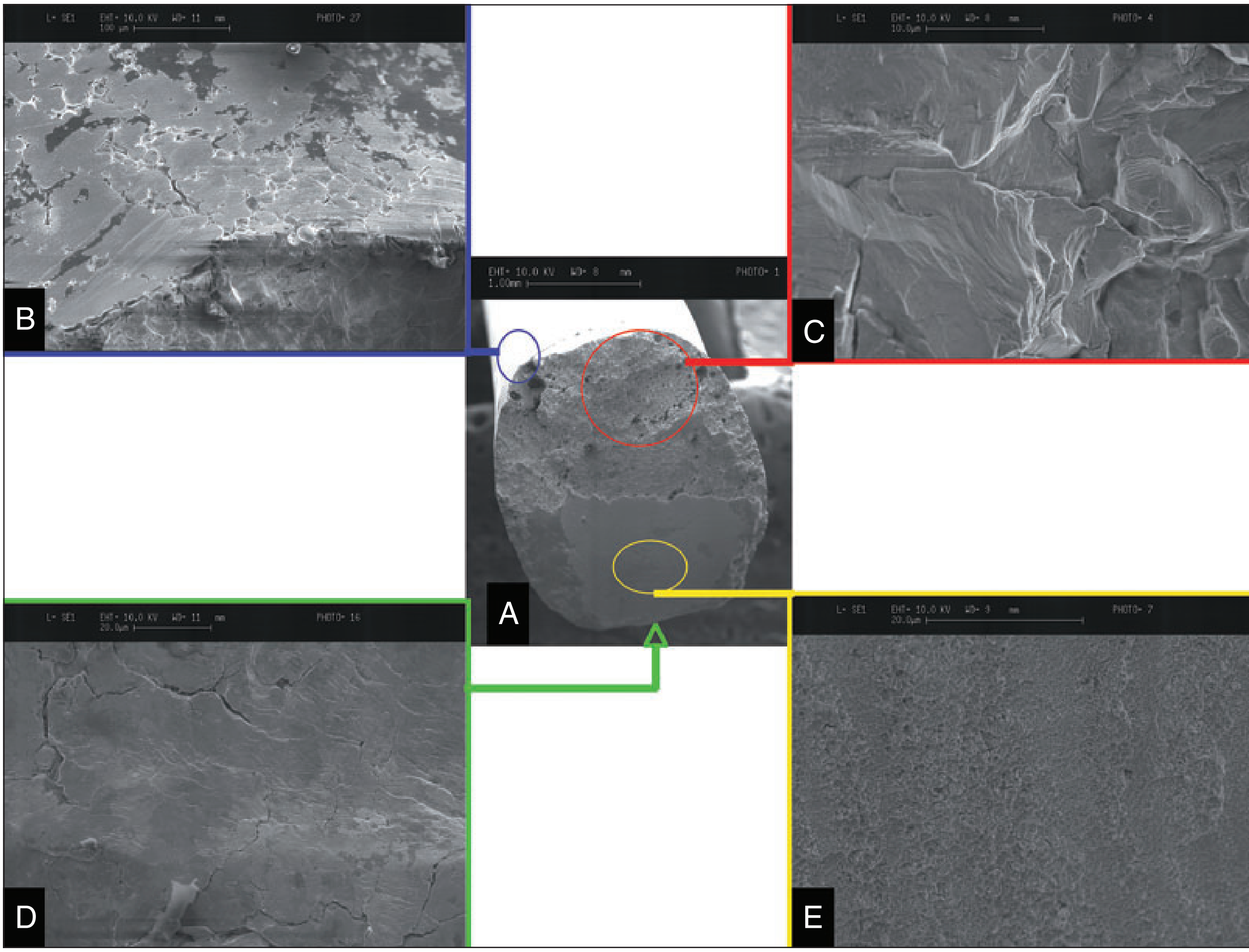

Figure 3 *A*, Overview of fracture surface of the cantilever bar (failure 1, Table 1). The upper portion shows that the crack had extended through the solder, whereas in the lower half, a smooth fracture at the solder-cylinder interface has occurred. *B*, Higher magnification of the surface features from which the crack appeared to initiate. These show regions of porosity along with corrosion of the grain boundary phase of the solder. *C*, Higher magnification of the crack extension through the solder appears to show fatigue striations running across the face of the break surface and cleavage type cracks branching in different directions. There is also the appearance of grain distortion. *D*, Creep and buckling of the solder in the zone of compression at the base of the solder joint. *E*, Fracture surface of the smooth lower portion of the failure showing fine grained intergranular fracture within the outer surface of the gold cylinder and not through the solder. This was evidenced by the color of the surface being gray, the same as the cylinder surface and not yellow as in the solder-solder fracture surfaces.

the solder and into the cylinder, resulting in the wall of the cylinder breaking out and remaining attached to the solder and bar (see Figure 6C). There was creep and buckling around the solder/cylinder junction on the sides of the cylinder. There appeared to be irregular transgranular fracture branching in different directions, indicating ductile overload. Intergranular fracture indicating brittle overload was apparent on the floor of the failed cylinder and the remainder of the failed cylinder wall. There was corrosion and early stages of progressive failure modes on the other intact abutment solder joints or abutment gold cylinders at the distal cantilever extension.

IB Group

All the IB showed evidence of varying degrees of progressive failure modes, namely corrosion, fatigue, and creep at least at one of the abutments in the area of the solder joint and/or the nonoxidizing gold cylinder. As in the FB group, there were no signs of progressive failure between the type IV gold bar and the gold solder. The start of a crack on the underside of the solder joint at the solder/cylinder junction was seen in one of the IB group when examined at the 5-year recall (Figure 7, A and B). There were limited signs of corrosion on the bar indicating that the process was predominantly being driven

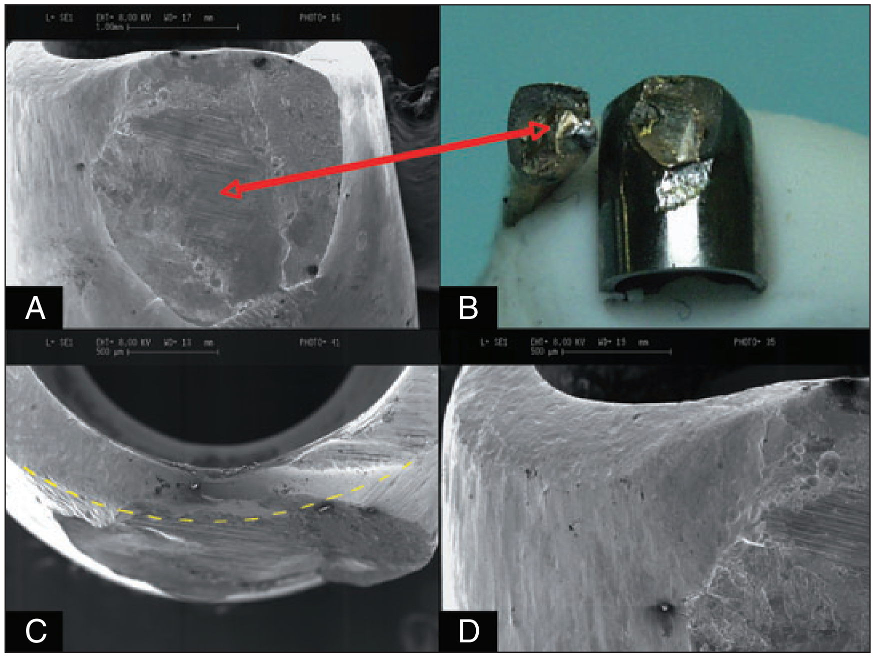

Figure 4 *A* and *B*, An overview of the center third of the joint where no solder flowed over the nonoxidizing gold cylinder surface during the manufacturing process. *C*, A top view of the nonoxidizing gold cylinder showing where the crack has extended into the cylinder. Missing area indicated by the dotted lines. *D*, Shows pitted top edge surface of nonoxidizing gold cylinder resulting from corrosion.

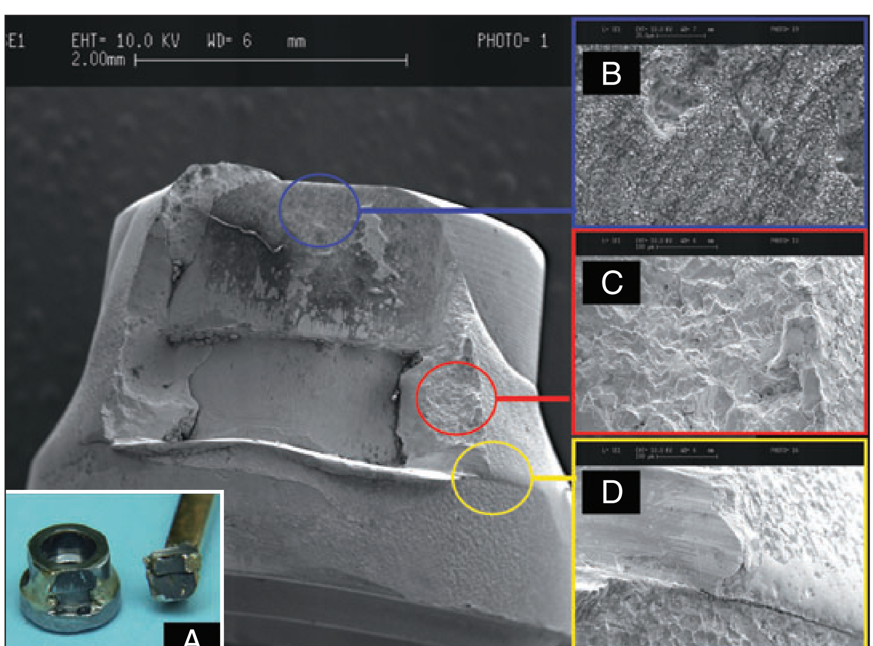

Figure 5 An overview of the fracture surface that has predominantly occurred through the cylinder at the solder-cylinder interface. This is evidenced by the gray-colored fine grained intergranular fracture that occurs with brittle overload (A and B). The fracture surface through the solder highlighted in (C) shows evidence of cleavage-type cracks with branching in different directions. The lower portion of the solder highlighted by (D) shows buckling and cracking where the solder joins the gold cylinder. Note the corrosion on the cylinder and solder outer surface.

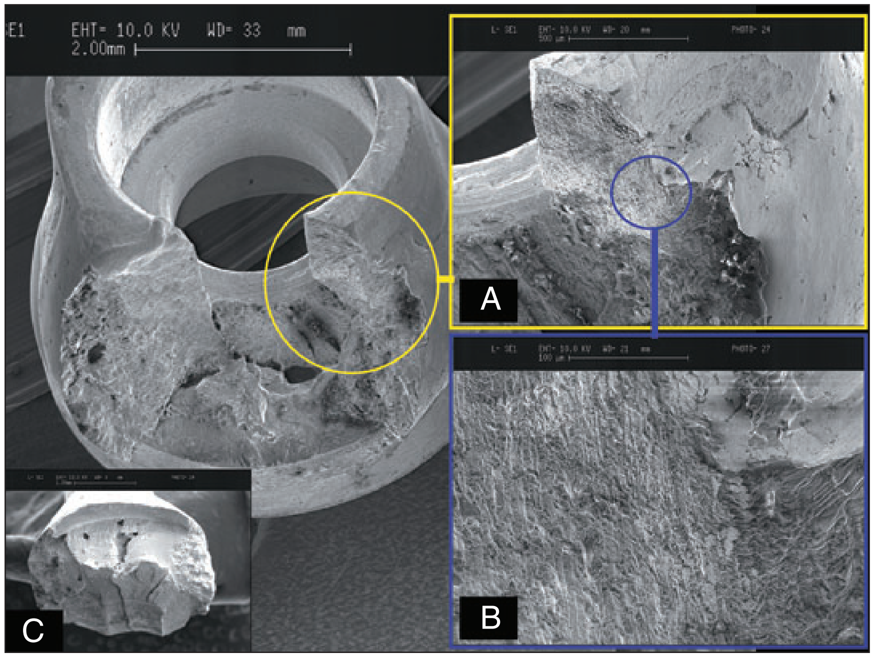

Figure 6 Fracture that has resulted in the cylinder wall breaking out and remaining attached to the solder and bar that was a distal extension cantilever of the overdenture bar. *A* and *B*, Shows an area of transgranular fatigue striations that may indicate the zone in which the crack initiated. *C*, Shows the inner cylinder wall still attached to the solder and bar.

by mechanical stresses. In another patient in the IB group when examined at the 2-year recall, extensive corrosion was seen to be taking place on the side of the nonoxidizing gold cylinder adjacent to the solder joint (see Figure 7, C and D). Evidence of stress corrosion cracking along with buckling and creep was seen on the underside of the cast gold milled bar adjacent to the junction of the cast-on nonoxidizing gold cylinder for

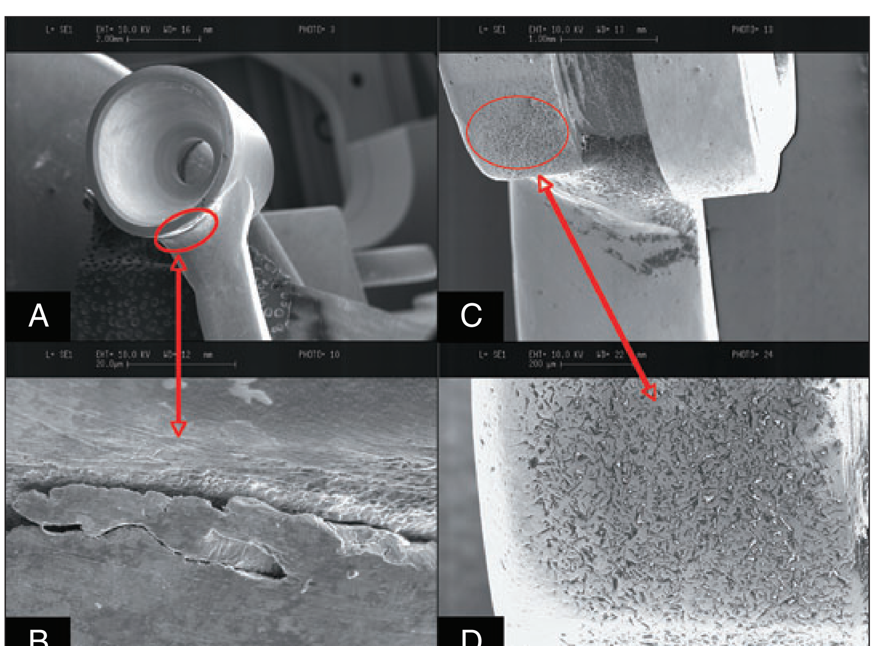

Figure 7 *A* and *B*, Shows the start of a crack system on the mucosa side of the solder joint at the solder/cylinder junction. *C* and *D*, Shows corrosion on the side of the cylinder adjacent to the solder joint, which also was showing signs of corrosion.

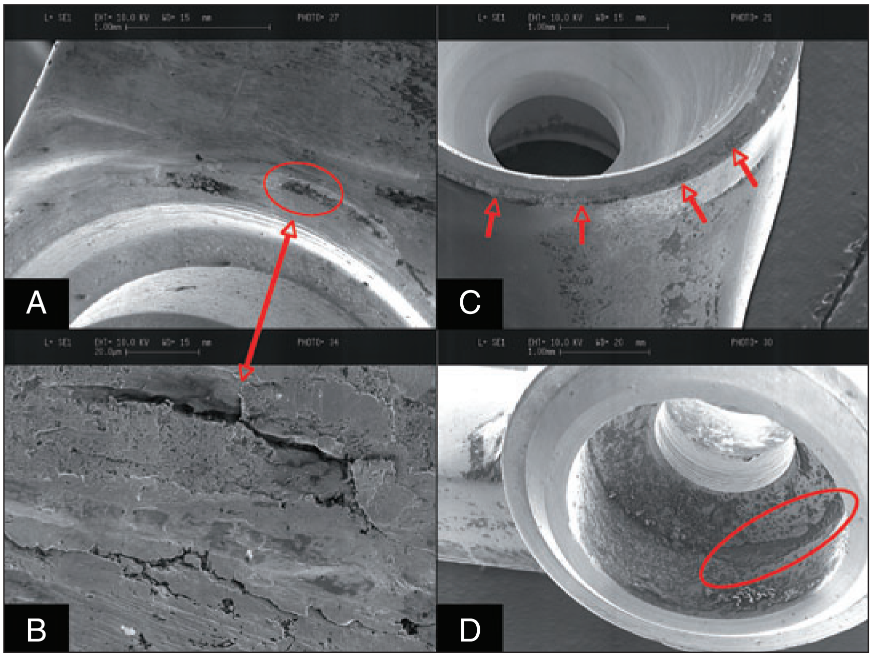

Figure 8 *A* and *B,* Shows stress corrosion cracking along with buckling and creep on the mucosa side of the cast gold milled bar adjacent to the junction of the cast-on nonoxidizing gold cylinder (taken at 5 years). *C,* Crevice corrosion on the edge of the fitting surface of the nonoxidizing gold cylinder where it seats onto the abutment or implant. The mucosa side of the solder is also showing evidence of corrosion. *D,* Extensive internal crevice corrosion.

another patient when examined at the 5-year recall (Figure 8, A and B). Similar evidence was detected on the underside (in contact with the mucosa) of the cast gold milled bar around the other four cast-on nonoxidizing gold cylinders. There was no evidence of progressive failure modes on the top side of the bar that was in contact with the denture and had easy access for cleaning. Figure 8C showed crevice corrosion on the edge of the fitting surface of the nonoxidizing gold cylinder where it connected onto the abutment or implant head when examined at the 2-year recall. The underside of the solder also showed evidence of corrosion. There was extensive internal crevice corrosion undermining the internal structure of the cylinder (see Figure 8D), as well as evidence of crevice corrosion on the outer edge of the fitting surface.

DISCUSSION

The aim of this research was to investigate the failure process using SEM analyses of soldered bars, as well as looking at a single cast milled bar removed from 11 patients who had been wearing implant overdentures for up to 5 years. This research shows that there is a corrosion process when these types of bars are used in the mouth. We do however acknowledge the limitations of this case series related to its limited sample size, numbers of implants supporting the bars, and the nature of the opposing arches. However, the metallic material used for the fabrication of the bars and the soldering materials were the same.

With regard to the location of the bar failures, the majority failed through the solder and through the cylinder at the solder-cylinder interface. The cylinder/cylinder failure showed a brittle overload mode of failure. When one postulates the stress distribution through a typical bar attachment system supporting an implant overdenture, the solder joint areas of the interconnecting bars are the area of highest stress concentrations during cyclic loading of the overdenture through mastication or clenching.[15] This is especially true where distal extension cantilever bars are included in the design.[14,32,33] The nature of the cylinder/cylinder failures at the solder-cylinder interface could indicate that a metallurgical reaction has taken place in this area during the soldering process. Wisckott and colleagues[26], in their study on the mechanical and elemental characterization of solder joints and welds, found diffusion between the elements of the solder and the parent metal during soldering that had effected the strength of the joints. There may have been a similar effect between the solder with its base metal elements diffusing into the nonoxidizing gold cylinder, which contained no base metal elements. This could be an attempt to achieve phase equilibrium between the various components of the solder and nonoxidizing gold cylinder during a reaction at elevated soldering temperatures, thereby creating a brittle layer.

For the progressive failure modes identified in this research, corrosion has been shown to be a key part of the failure process. This has been identified as an important factor in failure mechanisms by several authors who report that corrosion will reduce the strength and fatigue life of soldered joints.[15,34] The effects of cyclic loading from mastication can also increase the rate of corrosion, referred to as corrosion fatigue. The process of clenching and swallowing can reduce the load application frequency leading to longer periods during which the opened crack is in contact with saliva, and thereby a reduction in fatigue life.[29,35] The potential for corrosion would have also been increased by the combination of dissimilar alloys present in the area of the solder joints. This has been reported by other studies, and the presence of the lower gold content gold solder being sited near the fitting margins of the cylinders may have increased the potential for this to occur.[36–38] The other intact joints on the same FB often showed no corrosion, despite there having similar stress concentrations around the joints. A possible explanation could be that the corrosion process was an isolated galvanic condition for the failed solder joints in relation to the unique pH level of the saliva in the area around the abutment. A study by Bayramoglu and colleagues[39] showed the effects of various pH levels on the corrosion of dental alloys, noting that the inclusion of copper and tin in the alloy increased the rate of corrosion.

The SEM observations also showed that poor solder joints were not the primary cause of failure of overdenture bars, as has been previously reported.[17] As the overdentures have always been seen as a force transfer system, recognized authorities in the field advise that loads applied from the removable prosthesis to the bar will, in turn, be transmitted to the solder joint.[14] A study by Jemt and colleagues[40] showed that prostheses routinely connected to oral implants could demonstrate distortion between the framework and individual implants of up to several hundred microns. This residual stress in a bar attachment system after it has been torqued down, in combination with a galvanic couple, has been suggested as a cause of stress corrosion.[29] The nature of the loading conditions around the solder joint areas would be cyclic and multidirectional,[41] a combination of tension, compression, bending, and torsion due the various directions for the transfer of the load from the mastication process. According to Fontijn-Tekamp and colleagues[42], maximum loads on a mandibular implant overdenture can range from 160 N in the anterior region to just over 300 N in the posterior region. A study by van Kampen and colleagues[43] also showed that the mean maximum bite force recorded on bar attachment systems was as much as 300 N. These cyclic forces, when combined with the damage mechanisms of corroded surfaces on the solder and porosity defects within the solder, were probably enough to nucleate cracks at the surface of the solder and once this had propagated into the solder, the progressive failure mode of corrosion fatigue had commenced.[43] According to Lund,[44] this initiation process may occupy a significant portion of the overall time of the fatigue process, and this could account for the superficial evidence of fatigue, in the form of small micro-cracks, identified on all the non-FB attachment systems. Wear also does not appear to be a factor in the failure process. Creep in the form of buckling,[15,30] which was common to all failure sites and non-FB, was evident on the solder, in the areas of compression in terms of the direction of loading. This was probably due to the solder being more ductile than the bar or cylinder.

Instantaneous failure modes were observed on the fracture surfaces of the FB. Ductile overload[30] was observed predominantly in the solder. There was evidence of ductile overload where the failed part of the cylinder pulled away from the main part. However, where the solder, at the solder-cylinder interface, had pulled away from the cylinder, this showed evidence of brittle overload through the cylinder. Brittle overload[30] was observed in the FB group predominantly in the cylinders at the solder-cylinder interface. This type of failure was confined to the edge of the cylinder where the solder had wet the surface. It would appear that a metallurgical reaction, similar to that reported by Wiskott and colleagues,[26] has taken place in the cylinder edge that results in a thin brittle layer. Further research will be required to explain this observation.

Our findings also relate principally to mini-gold bars in type IV gold alloy that were egg-shaped (Dolder bar mini, height 2.30 mm Straumann code 048.411); or U-shaped in cross-section (NobelBiocare old code DCA

512 micro-U-shaped). It could therefore be argued that our findings are therefore not applicable to thicker overdenture bars, which are often used where there is sufficient interarch space due to residual ridge resorption. This relates to overdenture bars that have been also withdrawn from catalogues by some manufacturers (NobelBiocare old code DCA 514 macro U-shaped bars) as well as those still available from others (Dolder bar regular height 3.00 mm). Titanium bars for laser welding are also currently available as another option for overdenture bars (Straumann 048.466, 048.465). However, it should be noted that Wiskott[26] also found that, although laser welded joints were stronger than soldered joints when tested in tension, on the basis of fatigue resistance of the joints, there was no difference in strength between infrared solder joints, laser welds, torch, or furnace soldered joints. Casting the bar in one piece can reduce this problem. However, although we only had the one cast milled bar, it still showed evidence of the start of a progressive failure mode after 5 years of service.

CONCLUSIONS

A case series of SEM observations on both fractured and intact maxillary and mandibular overdenture bars soldered is presented. Findings revealed stress corrosion followed by corrosion fatigue as being key factors in the onset of the failure process. Although of clinical relevance, overestimated conclusions should not be drawn from these findings in view of the variation of parameters within the limited sample size.

ACKNOWLEDGMENTS

We acknowledge the ITI Research Foundation for the Promotion of Implantology, Berne, Switzerland (Grant for Clinical Research RCL 252/2002) for supporting this research. The Otago Centre for Electron Microscopy, University of Otago, Dunedin, New Zealand, is also acknowledged.

We are indebted to the participants in the Clinical Overdenture Research Project (CORP), Oral Implantology Research Group, Sir John Walsh Research Institute, School of Dentistry University of Otago, Dunedin, New Zealand. We thank also the patients of the graduate prosthodontic program, Discipline of Prosthodontics, Department of Oral Rehabilitation, of Dentistry University of Otago, Dunedin, New Zealand.

Finally, we acknowledge the generosity of the following: Nobel Biocare (Australia) Pty Ltd. and Southern Implants Ltd. South Africa for their previous support in terms of supplying the overdenture bars and implant components.

REFERENCES

1. Engquist B. Overdentures. In: Worthington P, Brånemark P-I, eds. Advanced osseointegration surgery: applications in the maxillofacial region. Chicago, IL: Quintessence, 1992:233–247.
2. Mericske-Stern R. Prosthodontic management of maxillary and mandibular overdentures. Chapter 10. In: Feine JS, Carlsson GE, eds. Implant overdentures: the standard of care for edentulous patients. Chicago, IL: Quintessence, 2003:83–98.
3. Palmqvist S, Sondell K, Swartz B. Implant-supported maxillary overdentures: outcome in planned and emergency cases. Int J Oral Maxillofac Implants 1994; 9:184–190.
4. Eckert SE, Carr AB. Implant-retained maxillary overdentures. Dent Clin North Am 2004; 48:585–601.
5. Lothigius E, Smedberg JI, De Buck V, Nilner K. A new design for a hybrid prosthesis supported by osseointegrated implants: 1. Technical aspects. Int J Oral Maxillofac Implants 1991; 6:80–86.
6. Naert I, Gizani S, van Steenberghe D. Rigidly splinted implants in the resorbed maxilla to retain a hinging overdenture: a series of clinical reports for up to 4 years. J Prosthet Dent 1998; 79:156–164.
7. Zitzmann NU, Marinello CP. Implant-supported removable overdentures in the edentulous maxilla: clinical and technical aspects. Int J Prosthodont 1999; 12:385–390.
8. Toljanic JA, Antoniou D, Clark RS, Graham L. A longitudinal clinical assessment of spark erosion technology in implant-retained overdenture prostheses: a preliminary report. J Prosthet Dent 1997; 78:490–495.
9. Kramer A, Weber H, Benzing U. Implant and prosthetic treatment of the edentulous maxilla using a bar-supported prosthesis. Int J Oral Maxillofac Implants 1992; 7:251–255.
10. Chan MF, Narhi TO, de Baat C, Kalk W. Treatment of the atrophic edentulous maxilla with implant-supported overdentures: a review of the literature. Int J Prosthodont 1998; 11:7–15.
11. Henry PJ. Future therapeutic directions for management of the edentulous predicament. J Prosthet Dent 1998; 79:100–106.
12. Henry PJ. A review of guidelines for implant rehabilitation of the edentulous maxilla. J Prosthet Dent 2002; 87:281–288.
13. Sadowsky SJ. Treatment considerations for maxillary implant overdentures: a systematic review. J Prosthet Dent 2007; 97:340–348.
14. Preiskel HW. Overdentures made easy: a guide to implant and root supported prostheses. London: Quintessence, 1996:108–137.

15. Waddell J, Ichim I, Lee H, Fangtao L, Payne AGT, Swain MV. Fatigue failures of bar-attachment brazed joints for implant-supported overdentures. Eng Fract Mech 2007; 74:1148–1159.
16. van Blarcom C, Bello A, Brown DT, et al. The glossary of prosthodontic terms. J Prosthet Dent. 8th ed. St Louis: Mosby, 2005.
17. Goodacre CJ, Kan JY, Rungcharassaeng K. Clinical complications of osseointegrated implants. J Prosthet Dent 1999; 81:537–552.
18. Waddell JN, Payne AG, Swain MV. Physical and metallurgical considerations of failures of soldered bars in bar attachment systems for implant overdentures: a review of the literature. J Prosthet Dent 2006; 96:283–288.
19. Shipley RJ, Becker WT. ASM failure analysis center. Ohio: ASM International, 2003. Available at: http://products.asminternational.org/hbk/index.jsp (accessed January 12, 2007).
20. Le May I. Examination of damage and material evaluation. Ohio: ASM International, 2003. Available at: http://products.asminternational.org/hbk/index.jsp (accessed January 12, 2007).
21. Callister WD. Materials science and engineering: an introduction. 7th ed. Hoboken, NJ: John Wiley & Sons, Ltd., 2007:210–211.
22. Reis L, Li B, De Freitas M. Analytical and experimental studies on fatigue crack path under complex multi-axial loading. Fatigue Fract Eng M 2006; 29:281–289.
23. Tanzer A. Determination and classification of damage. Ohio: ASM International, 2003. Available at: http://products.asminternational.org/hbk/index.jsp (accessed January 12, 2007).
24. Huang HM, Tsai CM, Chang CC, Lin CT, Lee SY. Evaluation of loading conditions on fatigue-failed implants by fracture surface analysis. Int J Oral Maxillofac Implants 2005; 20:854–859.
25. Wictorin L, Fredriksson H. Microstructure of the solder-casting zone in bridges of dental gold alloys. Odontol Revy 1976; 27:187–196.
26. Wiskott HW, Macheret F, Bussy F, Belser UC. Mechanical and elemental characterization of solder joints and welds using a gold-palladium alloy. J Prosthet Dent 1997; 77:607–616.
27. Al Jabbari YS, Fournelle R, Ziebert G, et al. Mechanical behavior and failure analysis of prosthetic retaining screws after long-term use in vivo. Part 4: failure analysis of 10 fractured retaining screws retrieved from three patients. J Prosthodont 2008; 17:201–210.
28. Lund RA. Macroscopic appearance of fatigue fracture. Ohio: ASM International, 2003. Available at: http://products.asminternational.org/hbk/index.jsp (accessed January 12, 2007).
29. Tanzer A. Forms of corrosion. Ohio: ASM International, 2003. Available at: http://products.asminternational.org/hbk/index.jsp (accessed January 12, 2007).
30. Becker W. Mechanisms and appearances of ductile and brittle fracture in metals. Ohio: ASM International, 2003. Available at: http://products.asminternational.org/hbk/index.jsp (accessed January 12, 2007).
31. Lampman S. Intergranular fracture. Ohio: ASM International, 2003. Available at: http://products.asminternational.org/hbk/index.jsp (accessed January 12, 2007).
32. Mericske-Stern R. Force distribution on implants supporting overdentures: the effect of distal bar extensions. A 3-D in vivo study. Clin Oral Implants Res 1997; 8:142–151.
33. den Dunnen AC, Slagter AP, de Baat C, Kalk W. Adjustments and complications of mandibular overdentures retained by four implants. A comparison between superstructures with and without cantilever extensions. Int J Prosthodont 1998; 11:307–311.
34. Darvell BW. Materials science for dentistry. 7th ed. Hong Kong: B.W. Darvell, 2002:285–299.
35. Callister WD. Materials science and engineering: an introduction. 6th ed. New York, NY: John Wiley & Sons, Ltd., 2003:220–221.
36. Al-Ali S, Oshida Y, Andres CJ, et al. Effects of coupling methods on galvanic corrosion behavior of commercially pure titanium with dental precious alloys. Biomed Mater Eng 2005; 15:307–316.
37. Guindy JS, Schiel H, Schmidli F, Wirz J. Corrosion at the marginal gap of implant-supported suprastructures and implant failure. Int J Oral Maxillofac Implants 2004; 19:826–831.
38. Lemons JE, Lucas LC, Johansson BI. Intraoral corrosion resulting from coupling dental implants and restorative metallic systems. Implant Dent 1992; 1:107–112.
39. Bayramoglu G, Alemdaroglu T, Kedici S, Aksut AA. The effect of pH on the corrosion of dental metal alloys. J Oral Rehabil 2000; 27:563–575.
40. Jemt T. In vivo measurements of precision of fit involving implant-supported prostheses in the edentulous jaw. Int J Oral Maxillofac Implants 1996; 11:151–158.
41. Wiskott HW, Nicholls JI, Belser UC. Stress fatigue: basic principles and prosthodontic implications. Int J Prosthodont 1995; 8:105–116.
42. Fontijn-Tekamp FA, Slagter AP, van't Hof MA, et al. Bite forces with mandibular implant-retained overdentures. J Dent Res 1998; 77:1832–1839.
43. van Kampen FM, van der Bilt A, Cune MS, Bosman F. The influence of various attachment types in mandibular implant-retained overdentures on maximum bite force and EMG. J Dent Res 2002; 81:170–173.
44. Lund RA. Fatigue fracture processes. Ohio: ASM International, 2003. Available at: http://products.asminternational.org/hbk/index.jsp (accessed January 12, 2007).