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Applications of Current Technologies for Nondestructive Testing of Dental Biomaterials

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1. Introduction

Dental biomaterials consist of a wide range of synthetic products that are normally used to restore patients' oral health, function and aesthetic appearance. Generally, dental biomaterials are classified on the basis of their atomic bonding into metallic, ceramic, polymer and composite materials. In addition to this classification, biomaterials can be classified according to their interactions with the surrounding oral tissues (Mano et al. 2004). Based on the tissue responses, biomaterials can be divided into three different categories commonly known as bioinert, bioactive and bioresorbable materials.

- Bioinert materials are materials that have minimal interactions with the surrounding tissues, such as partially stabilized zirconia, alumina, pure titanium and some of its alloys, some grades of stainless steel and ultra high molecular weight polyethylene.
- Bioactive materials are materials that start to interact positively with the surrounding hard and sometimes soft tissues after placement inside a biological body. Synthetic hydroxyapatite $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$ and bioglass are the best representative examples of commonly used bioactive materials.
- Bioresorbable materials are materials that begin to progressively dissolve and slowly become replaced by the adjacent biological tissues after placement or implantation inside a biological body. Polylactic-polyglycolic acid copolymers and tricalcium phosphate $[\text{Ca}_3(\text{PO}_4)_2]$ are two examples of the most commonly used bioresorbable materials.

Further to these previous classifications of dental biomaterials, it is important to mention that the final products normally placed in the oral cavity are produced in two different ways. The first involves industrial line production, wherein thousands of identical dental

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devices are manufactured, such as dental implants, endodontic files and orthodontic wires/brackets. The second is the production of custom-made devices that are produced in dental laboratories, such as crowns, fixed partial dentures, removable partial dentures, complete dentures and orthodontic devices (Figure 1).

As with any industrial application, the structural integrity of dental devices has to be tested to preserve the reliability of function and avoid premature failures. This testing starts with quality control aiming to discard any defective items, while the end products should comply with safety regulations and materials specifications (i.e. ISO standards). Information for assuring proper quality is acquired through destructive and non-destructive testing. These techniques are easily distinguished from each other, as the latter leaves the tested devices undamaged and suitable for additional testing and/or permanent usage in patients. Non-destructive testing (NDT) involves a broad spectrum of analytical techniques, including macroscopic/microscopic visual inspection, eddy current testing, radiography, X-ray computed tomography (XCT), resonance frequency analysis (RFA) and many others. NDT aims to qualitatively and/or quantitatively characterize the tested devices by detecting,



Fig. 1. a) Representative examples of industrially-made dental devices: 1) orthodontic archwire made of Ni-Ti alloy, 2) endodontic file made from Ni-Ti alloy, 3) Mini-orthodontic implant made of cp-Ti and 4) dental implant made of Ti. b) Industrially-made orthodontic brackets fabricated from stainless steel alloy. c) Custom-made ceramo-metal crowns. d) Custom made removable partial denture made of Cr-Co alloy and acrylic resin.

locating and sizing any external/internal structural defects. The acquired information is then assessed to evaluate whether the tested devices meet acceptable criteria or whether they should be rejected. Taking advantage of the NDT capabilities, the quality of the end products is increased while the level of reliability is enhanced. The application of these sophisticated NDT methods can easily be conducted industrially to produce acceptable dental devices. However, conducting extensive systematic quality control for custom-made dental devices is restricted owing to 1) the tremendous increase in relative costs, 2) the need for availability of specifically designed testing equipments in dental offices and laboratories and 3) the need for well-trained dentists and dental technicians to operate these equipments. Besides all these factors, if proper NDT is applied routinely to custom-made dental devices, it will dramatically increase the total cost of already expensive dental services.

Although there are a number of limiting factors for routine application of NDT in dentistry, NDT has a variety of important applications in the dental field. The best example is X-ray radiography, which is used for the detection of pores that are typically located in thin regions of cast custom-made dental devices (i.e. clasp shoulders of a cast metal removable partial denture framework). The early detection of pores at these critical regions and stage will allow the dentist and/or dental technician to correct the problem before the final delivery of the prostheses to the patients. The existence of such pores will lead to catastrophic premature failure in the oral cavity. In research applications, NDT contributes significantly to the determination of adverse effects of the oral environment on dental biomaterials/devices and vice versa. In addition, NDT is very helpful in studies of the interaction mechanisms between the oral environment and dental biomaterials as a result of intraoral aging. A variety of NDT methods can be used to fully characterize dental devices preoperatively (as received) and after retrieval from the oral cavity by tracking the occurrence of any changes during intraoral aging. Stereomicroscopy, variable pressure SEM (VPSEM) without the need for a conductive coating and X-ray microanalysis have been used to monitor the morphological and elemental alterations after intraoral aging of dental devices. In addition, computed X-ray micro-tomography (micro-XCT) has been used to correlate the locations and sizes of internal defects found preoperatively in all ceramic bridges with the fracture origin under clinical conditions. Such information acquired from micro-XCT regarding the defect locations will provide tremendous insights into the underlying mechanism of intraoral degradation. Other examples for applications of NDT in dentistry are 1) noninvasive and *in situ* testing of intraoral implant stability utilizing RFA and 2) detection of hidden or sub-surface caries (tooth decay) by utilizing X-radiography and laser technology measuring laser fluorescence within the tooth structure.

The aim of this chapter is to present and discuss the applications of current technologies for NDT of dental biomaterials covering a wide range of NDT techniques and their impacts on daily dental practice, noninvasive diagnosis and dental biomaterials research.

2. Applications of NDT for quality assurance purposes during dental treatment

Commonly, NDT techniques are performed by dentists and/or dental technicians to ensure the proper quality of custom-made dental devices. For example, they carry out routine checks by the naked eye or using a stereoscope for the marginal integrity of dental restorations (crowns) for precision before the restorations are delivered permanently to the patients. However, it is important to mention that precision in dentistry is a subjective term

and varies from one dentist to another. This means that proper precision and acceptability are dependent on a dentist's personal experience and skills. Therefore, this type of testing/inspection is optional and in many situations is performed without specific requirements to accept or reject custom-made dental devices (e.g. crowns). Internal defects in cast and welded metallic custom-made devices are not uncommon and X-ray testing is performed for early detection of such defects. This section will present the dental applications of stereoscopic and X-ray examinations and testing.

2.1 Stereomicroscopic examination and testing

Stereomicroscopic examination is performed routinely by dental technicians and/or dentists to evaluate the quality of recently fabricated custom-made dental devices (e.g. crowns). Detection of any problems at this stage will allow for proper correction before the final prosthesis insertion in the patient's mouth. A recent study found that implant retaining screws deteriorate over a period of time when they are used to hold a dental prosthesis in a patient's mouth (Al Jabbari et. al, 2007a). Therefore, the authors encouraged dentists who provide extensive implant treatment in their practice to equip their offices with a stereomicroscope to enable regular evaluation of the quality of the tiny retaining implant screws at follow-up appointments. A low power stereomicroscope was found to be a powerful and useful tool for evaluating the quality of the external structures/surfaces of tiny dental devices (e.g. prosthetic retaining screws) (Al Jabbari et. al, 2007a). As illustrated in Figure 2, the stereomicroscope was able to clearly reveal the damage and deterioration of an implant screw head and threads, whereas it is almost impossible for a dentist to observe such damage and deterioration under the naked eye. The great advantage of performing this type of NDT in dental offices is that it will allow dentists to replace any severely damaged or deteriorated retaining screws with new ones. Failure to detect such deterioration and damage may lead in the future to a more complicated and expensive dental treatment for patients (Al Jabbari et. al, 2007b).

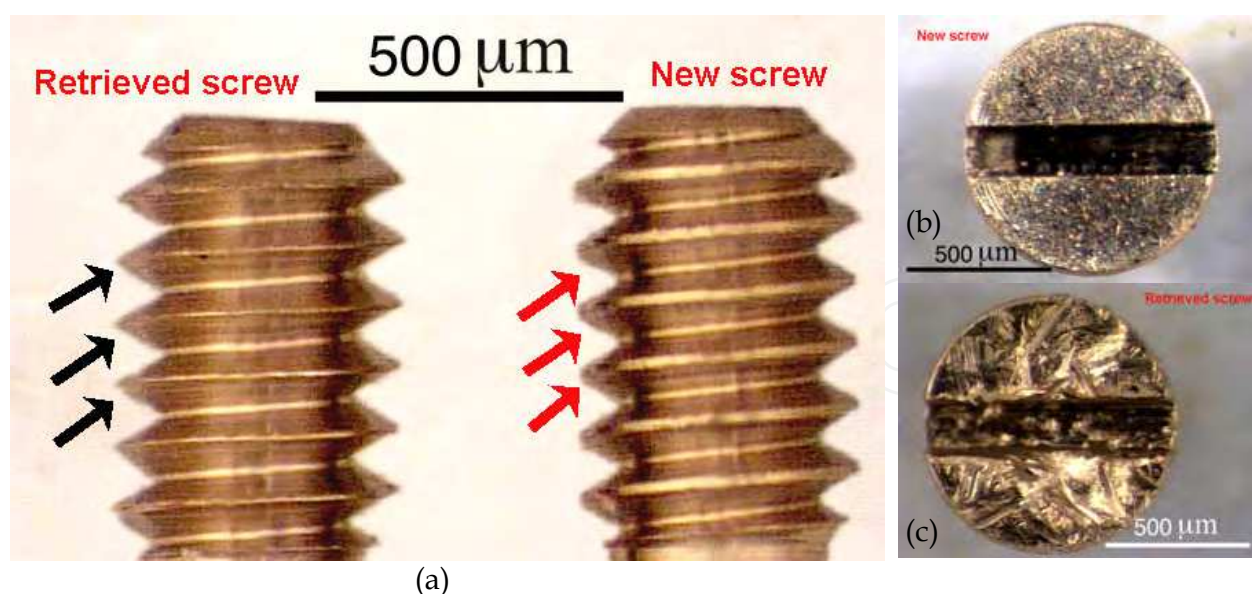


Fig. 2. Threaded segment (a) and slotted head segment (b) & (c) of new and retrieved implant retaining screws examined under stereomicroscope. Examination of these tiny dental implant devices reveals significant threads deterioration/thinning “black arrows” and screw head damage “(c)” when compared to the intact threads profile “red arrows” and normal slotted head (b).

As mentioned previously, dental technicians routinely evaluate the quality of their fabricated devices. For example, they use a stereomicroscope to examine devices made by casting. If they detect any external large casting porosity, they will correct and repair the problem by filling the pores with solder materials or they may need to remake the whole casted device before they pass it for clinical application. In addition, they regularly evaluate the passivity of the fit of their cast prosthesis superstructure utilizing a stereomicroscope. If they detect any misfit between the cast superstructure and the supporting teeth and/or implants, they will correct the problem using recasting, soldering, welding and electro-discharging machining techniques (Contreras et al. 2002; Ntasi et al. 2010; Romero et al. 2000; Zinelis 2007).

2.2 X-ray testing

Many dental devices (such as crowns, and fixed and removable partial dentures) are traditionally manufactured by casting dental alloys. Recently, the preparation of metal-free crowns and bridges has introduced the concept of casting ceramic materials. However, the mechanical stability and biocompatibility of dental devices depend on the properties of the materials and on the accuracy of the manufacturing process. Unfortunately, the dental casting procedure unavoidably leads to the development of pores in dental cast frameworks owing to gas entrapment or shrinkage, which may adversely affect the quality and efficacy of dental devices. The development of undesirable porosity is dependent on various factors and is a common complication for precious, semiprecious and base contemporary dental alloys (Elliopoulos et al. 2004; Li et al. 2010; Neto et al. 2003; Ucar et al. 2011; Zinelis 2000). This may negatively affect the long-term mechanical stability. For example, when there are cast external porosities, corrosion resistance decreases because of crevice formation and plaque accumulation in the oral cavity.

In industrial applications, internal voids can be readily investigated by employing X-ray examination, and the same technique has been adopted in dental practice as a non-destructive method for the same purposes. Pores can be easily distinguished as dark regions on radiographs, thereby providing significant information for the size, location and distribution of imperfections. The same methodology can be readily applied to identified internal voids in dental cast frameworks (Dharmar et al. 1993; Eisenburger et al. 2002; Eisenburger et al. 1998; Elarbi et al. 1985; Mattila 1964; Wictorin et al. 1979). However, the visibility of voids and the picture quality depend on the combination of the material to be tested and the analytical conditions applied for X-ray testing (Eisenburger & Addy 2002).

Going back to the principle of this technique, it must be noted that the attenuation of a narrow beam of monoenergetic photons with specific E and intensity I_0 passing through a homogeneous material of thickness t is determined by Lambert's law:

$$I = I_0 e^{-\mu(\rho, Z, E)t} \quad (1)$$

where I is the photon intensity that goes out to the sample, and μ is the linear attenuation coefficient that depends on the material density, atomic number Z and beam energy. Therefore, the X-ray absorption depends on the atomic number, the density of the material and the energy of radiation. Accordingly, different dental alloys can be penetrated by X-rays to different extents during testing. As stated above, various precious, semiprecious and base

metal alloys are used in the dental field that have different elemental, mechanical and physical properties (Roberts et al. 2009; Wataha 2002). Table 1 shows some representative types of dental alloys with densities ranging from 4.51 g/cm³ for Ti to 19.3 g/cm³ for pure Au. The vast majority of dental frameworks are produced by casting of precious and base metal alloys (Roberts et al. 2009) with the exception of pure gold for use in dentistry, which employs an electroforming technique (Vence 1997). As can be expected from equation (1) and the density values of the base metal alloys in Table 1, lower levels of X-ray absorption facilitate X-ray penetration. Low absorption coefficients and a high energy beam are needed to penetrate the thick metallic parts of cast dental frameworks. Figure 3 demonstrates the attenuation coefficients of some of the dental alloys presented in Table 1. As can be seen in Figure 3, the absorption coefficients decrease with increasing beam energy. This is not the case for pure Au and Au-based dental alloys where the absorption coefficient rises at the energy of 80 kV because the K absorption edge limits the penetration of Au and Au-based dental alloys to 0.6 mm (Eisenburger & Tschernitschek 1998). Non-precious and base dental alloys such as Ni-Cr, Co-Cr and commercially pure Ti (cpTi) can be penetrated by up to several millimeters depending on the accelerating voltage and exposure time (Eisenburger & Addy 2002; Eisenburger & Tschernitschek 1998).

Brand name	Mass content (%)	Type	Density (gr/cm ³)
Electroforming*	Au: 99.9	Pure Au	19.3
IPS d.SIGN 98	Au:85.9, Pt:12.1, Zn:1.5, In<1.0 Ir<1.0, Fe<1.0, Mn<1.0, Ta<1.0,	High Au	18.9
Degudent U94*	Au:76.0,Pt:9.6,Pd:8.9,Ag:1.2,Cu:0.3 Sn:0.8,In:1.5,Ir:0.1,Re:0.2,Ta:0.2.	High Au	17.9
Degulor M*	Au:70.0,Ag:13.5,Au:8.8,Pt:4., Pd:2.0, Zn:1.2, Ir: 0.1	High Au	15.5
Degupal G*	Pd:77.3, Ag:7.2, Au:4.5, Sn:4.0, Ru: 0.5; Ga: 6.0; Ge: 0.5	Pd based	11.7
4 all	Ni:61.5, Cr:25.7, Mo:11.0, Si:1.5, Mn<1.0, Al<1.0	Ni-Cr	8.4
IPS d.SIGN 30	Co:60.2,Cr:30.1,Ga:3.9,Nb:3.2 Si:0.9, Mo:0.6, Fe:0.5, B:0.3, Li<1.0	Co-Cr	7.8
Ti*	Ti:balance,O< 0.2,N< 0.06, C<0.08, H< 0.013, Fe < 0.25	cp Ti (gradeII)	4.5

Table 1. Brand names, elemental compositions, alloy types and densities of some representative dental alloys used for the production of metalloceramic crowns and bridges. The alloys are sorted in descending order of the density. The attenuation coefficients of the alloys indicated by asterisks are shown in Figure 3.

As examples, Figure 4 shows dental devices casted from grade II cpTi and analyzed by X-rays at 70-kV tube voltage, 8-mA beam current and 0.32-s exposure time. In Figure 3a, it can be seen that large pores are located at the connector areas of a cast framework for a fixed partial denture. Similar sized pores can be seen in cast rectangular specimens used for the determination of metalloceramic bonding strength values (Figure 4b). The spherical shape of these pores is a strong indication of gas entrapment, which is a typically reported problem

when cpTi and Ti alloys are cast (Elliopoulos et al. 2004; Zinelis 2000). Figures 4c and 4d show spherical pore formation on a cast framework for a removable partial denture located critically at the shoulder of a circlet clasp, which is considered to be a common region for such pore formation.

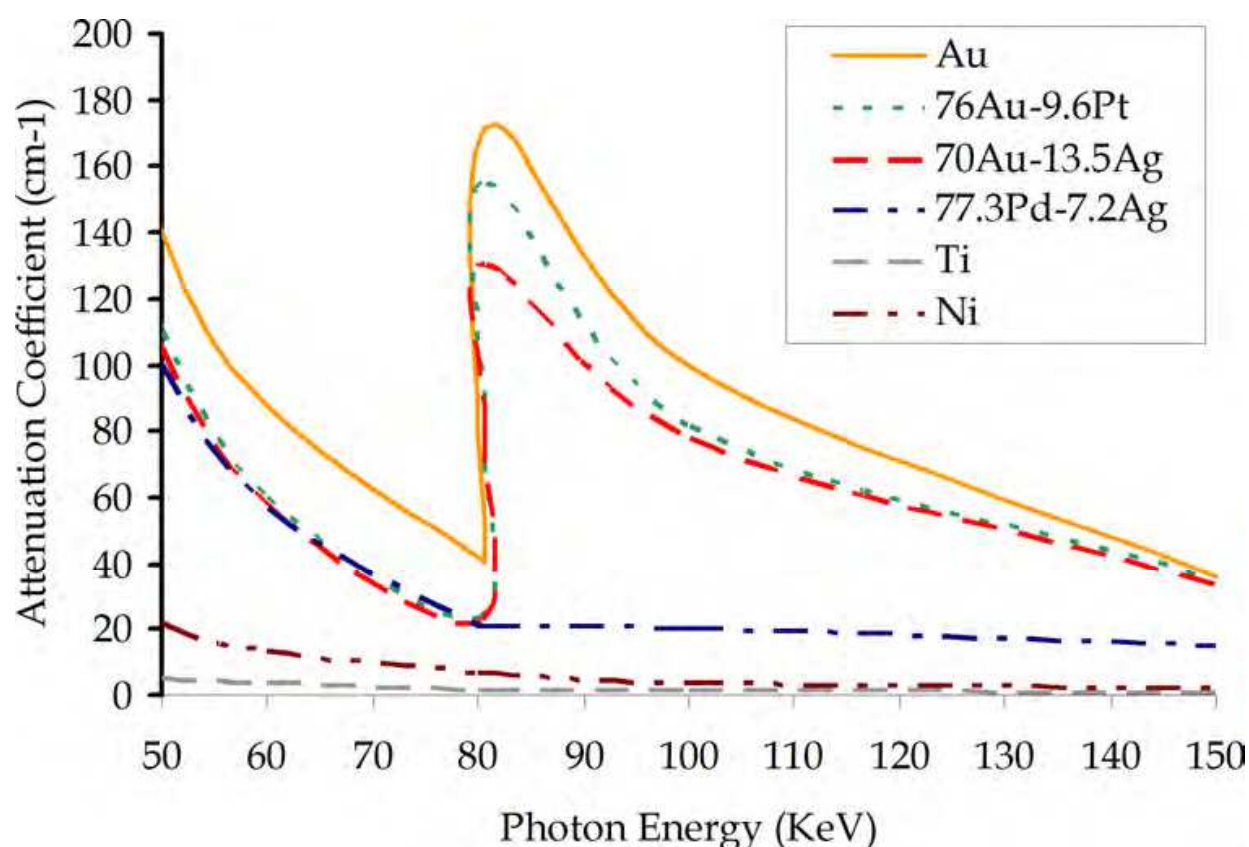


Fig. 3. Mass attenuation coefficient of three dental alloys (Eisenburger & Tschernitschek 1998). The same values for pure Au, Ni and Ti are presented for comparison purposes (Hubbell et al. 1996).

The main advantage of radiographic X-ray testing is the ability to provide quick valuable information about the quality of the metal framework casting by revealing the locations, numbers and sizes of internal defects that are not possible to detect by visual inspections. The occurrence of internal defects/porosity at critical regions such as the clasp shoulders of cast removable partial denture frameworks will lead to premature clinical failures. Therefore, early detection will allow proper correction of the problem prior to final delivery of a prosthetic device to a patient.

Previous studies have reported that fractures and premature failures of removable partial denture frameworks range from 16% to 19% owing to the occurrence of internal porosity in cast Co-Cr frameworks (Dharmar et al. 1993; Elarbi et al. 1985; Wictorin et al. 1979). In addition, they revealed that the frequencies of the common locations of these defects were 22% to 73% at major connectors, 5% to 43% at clasps/clasp shoulders and 6% to 8% at minor connectors (Dharmar et al. 1993; Elarbi et al. 1985). Therefore, and because of the high rates of occurrence of such defects, dentists and/or dental technicians are encouraged to perform radiographic X-ray inspections at early stages of removable partial denture fabrication.

Early detection of these casting defects and imperfections may allow easy repair or simple remaking of the metal framework. On the other hand, late detection may mandate remaking of the entire removable prosthesis, which is considered to be a costly choice to be performed by dentists, to avoid intraoral premature failures of a removable prosthesis.

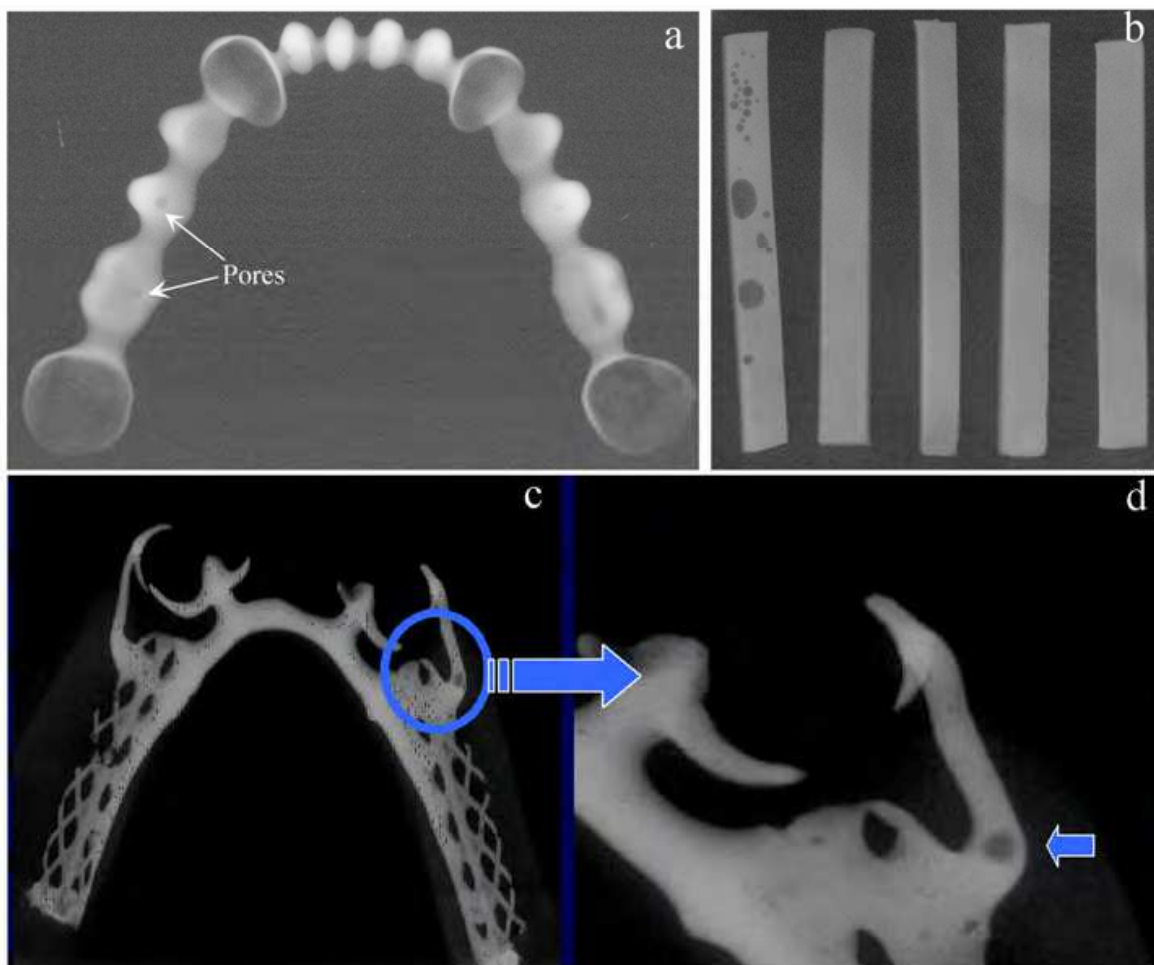


Fig. 4. X-ray images of dental casting. a) A dental cast framework for fixed partial denture, b) cast specimens for testing metal-ceramic bond strength c) a cast framework for removable partial denture and d) High magnification of the highlighted region in (c) and it shows internal porosity occurrence (small arrow) at the clasp shoulder.

Another valuable dental application of radiographic nondestructive X-ray testing is in retrieval analysis studies. Conventional dental X-ray units can be readily used for X-ray analysis of dental alloys, except for pure Au and Au-based alloys where the penetration depth is limited to approximately 0.6 mm and thus increasing acceleration voltage to 120 kV is not possible with conventional dental X-ray machines. Microfocus X-ray systems (CRX 1000/CRX 2000; CR Technology Inc., Aliso Viejo, CA, USA) have been used to detect the occurrence of internal defects in prosthetic retaining implant screws made of gold-based alloys (Al Jabbari et al, 2007a). For NDT, utilization of a microfocus X-ray machine is possible and very valuable for evaluating various tiny dental devices made from precious, semiprecious and non-precious alloys. However, this type of machine is known to be mainly useful for dental biomaterials research purposes.

3. Applications of NDT for research purposes in the dental biomaterials field

Besides the valuable applications of NDT in quality assurance of dental devices, NDT makes significant contributions and has important applications in the dental biomaterials research field. Normally, dental biomaterials in the oral cavity are exposed to various aggressive conditions. When biomaterials are placed intraorally in the form of filling materials or prosthetic appliances, they go through a variety of degradation mechanisms such as fatigue, wear, corrosion and discoloration. Therefore, studies of the degradation mechanisms of biomaterials are important toward the design of new biomaterials with increased efficacy and longevity.

Laboratory or *in vitro* testing is widely applied to dental biomaterials to determine the properties of the materials. However, *in vitro* testing cannot provide any reliable information that can predict the *in vivo* behavior of biomaterials because the conditions of the oral environment cannot be simulated experimentally in research laboratories. Accordingly, NDT can be effectively used over a long period of time to monitor the occurrence of changes in a specific dental biomaterial or device resulting from intraoral aging. Generally, NDT of a retrieved specific dental biomaterial or device that has been placed in a patient's mouth for a reasonable time and comparison with the properties of a new (unused) biomaterial/device will provide more useful and significant information about the degradation mechanism resulting from long-term use *in vivo*. Under this general concept, a variety of NDT methods and techniques have been developed such as micro-XCT, VPSEM-EDS, optical profilometry and X-ray diffraction (XRD).

The main two limiting factors in conducting such research protocols are ethical and cost reasons. For example, a permanently placed filling dental biomaterial cannot be retrieved from the mouth for only research purposes. Retrieval of a biomaterial and replacement with a new one will subject the tooth to additional unnecessary clinical procedures. Multiple clinical procedures will cause repeated insults to a specific tooth that may lead to pulpal irritation and/or necrosis. Needless to say, that is ethically unacceptable. Similarly, a successful dental appliance or device cannot be retrieved from the mouth solely to conduct NDT before it fails, since making a new one is costly for the patient and there is no guarantee that the newly fabricated device will be as successful as the first one.

There are two additional obstacles that may also make the performance of NDT in retrieved dental biomaterials infeasible. First, it requires frequent patient follow-ups before the biomaterials and/or devices are retrieved. Unfortunately, not all patients will accept many follow-ups for research purposes only. Second, many retrieved dental biomaterials and/or devices are unsuitable for the conduction of certain types of NDT. For example, XRD analysis requires flat surfaces of a few square millimeters in dimension, a requirement that is hard to fulfill in dental devices.

3.1 Micro-XCT

Currently, computed tomography is extensively used in the medical field for diagnostic/treatment purposes. During the last two decades, new bench-top models have been introduced for use in the characterization of materials that employ similar principles to medical computed tomography. The only difference is that the bench-top models have an isotopic resolution capable of reaching a few tens of nanometers. Contrary to medical

computed tomography machines, the specimens tested with bench-top models can be rotated while the detector and X-ray source are fixed within the machine. The micro-XCT scanning produces hundreds of horizontal slices for a tested specimen, which are then used to reconstruct the entire specimen. Reconstruction of a specimen is accomplished by two reconstruction algorithms commonly known as iterative and filtered back projection methods. In addition, computer software can be utilized in the development of three-dimensional models, pseudocoloring and quantitative determination of geometrical features of an irregular dental biomaterial device.

Figure 5 shows a good example of NDT utilizing a micro-XCT analysis of a fixed partial denture (FPD). It reveals the importance of this tool for nondestructively analyzing the internal structure of the whole ceramic FPD. The FPD was analyzed prior to permanent cementation of the prosthesis in the patient's mouth. The analysis revealed that the joining procedure of the three different parts of the alumina core was not done properly because of the entrapment of large voids at and within the bulk of the cementing material (Figure 5d). Unfortunately, after final insertion of the FPD in the patient's mouth, it did fail at the connector area after being in service for a short period of time. Therefore, it can be said that micro-XCT is a powerful tool for evaluating the quality of industrially and/or custom-made dental devices and for failure analysis of dental biomaterials.

3.2 SEM-VPSEM-EPMA

Scanning electron microscopy (SEM) combined with electron probe microanalysis (EPMA) is considered to be a powerful analytical tool for providing morphological and elemental information about tested samples at low (6×) and high (150,000×) magnifications. SEM is able to bridge the gap between optical stereomicroscopy and transmission electron microscopy. Recent advancements in SEM manufacturing technology can provide imaging of non-conductive specimens (low-vacuum SEM) and samples at 99% relative humidity (environmental SEM). These new operating modes are also known as VPSEM and confer tremendous capabilities to SEM. Additional information regarding the operation principles and applications of these new SEM models can be found in relevant previous reports (Bergmans et al. 2005; Danilatos; Danilatos 1991; Danilatos 1993; Danilatos 1994; Danilatos et al.; Kodaka et al. 1992).

In dentistry, brazing is the main joining technique for making metallic orthodontic appliances. A space maintainer is an example of the most commonly used orthodontic appliances. This appliance is made of two stainless steel tooth bands joined by a stainless steel orthodontic wire. The orthodontic wire and the two bands are joined by brazing utilizing low fusing silver brazing alloys (Figure 6). Figure 7 shows a high magnification SEM photomicrograph of an orthodontic space maintainer appliance, revealing that the soldered area joins the stainless steel bands to the orthodontic wire. NDT utilizing X-ray EDS analysis was performed at that area at two different times (before and after dental treatment). The purpose of the NDT and the analysis was to determine the effects of long-term use *in vivo* on the Ag-based brazing alloy. Small porosities (indicated by arrows in Figure 7) were used to identify the area for X-ray EDS analysis. The two spectra obtained at the two different times are shown in Figure 8, and reveal significant decreases in the Cu and Zn composition after intraoral aging.

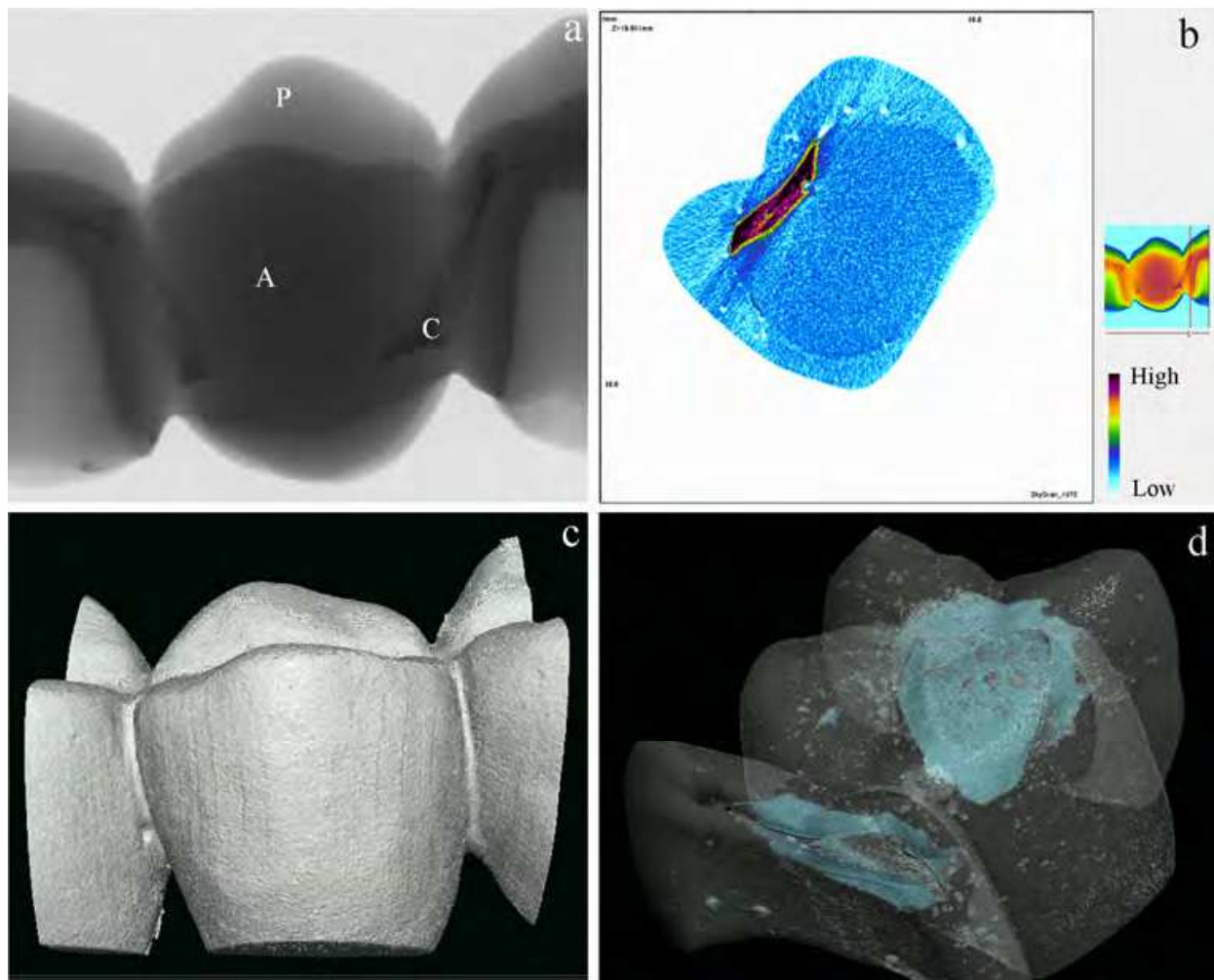


Fig. 5. Micro XCT analysis of a fixed partial denture (FPD) that was fabricated from all ceramic materials. The core of the FPD was made from alumina that was veneered with dental porcelain. **a)** FPD X-ray image before the FPD was cemented in the patient's mouth showing (A) the core alumina, (B) the veneering porcelain and (C) the connector area joining the three unites of the FPD. It is easy to distinguish between the three parts because the differences in X-ray absorption. **b)** A pseudocoloring reconstruction of a perpendicular cross section for the FPD showing the alumina core, the veneering porcelain and the material used for cementation at the connector area. Pores are easily identified as white circle areas in the regions of porcelain layer and at the core porcelain interface. Red line located on the small attached image indicates the cross sectional plane while the bar indicates the absorption scale. **c)** 3D image of the reconstructed structure after digital processing helpful in total volume determination. **d)** Alternative 3D image showing the distribution of internal pores in dental porcelain and the occurrence of big voids near and within the cement layer.

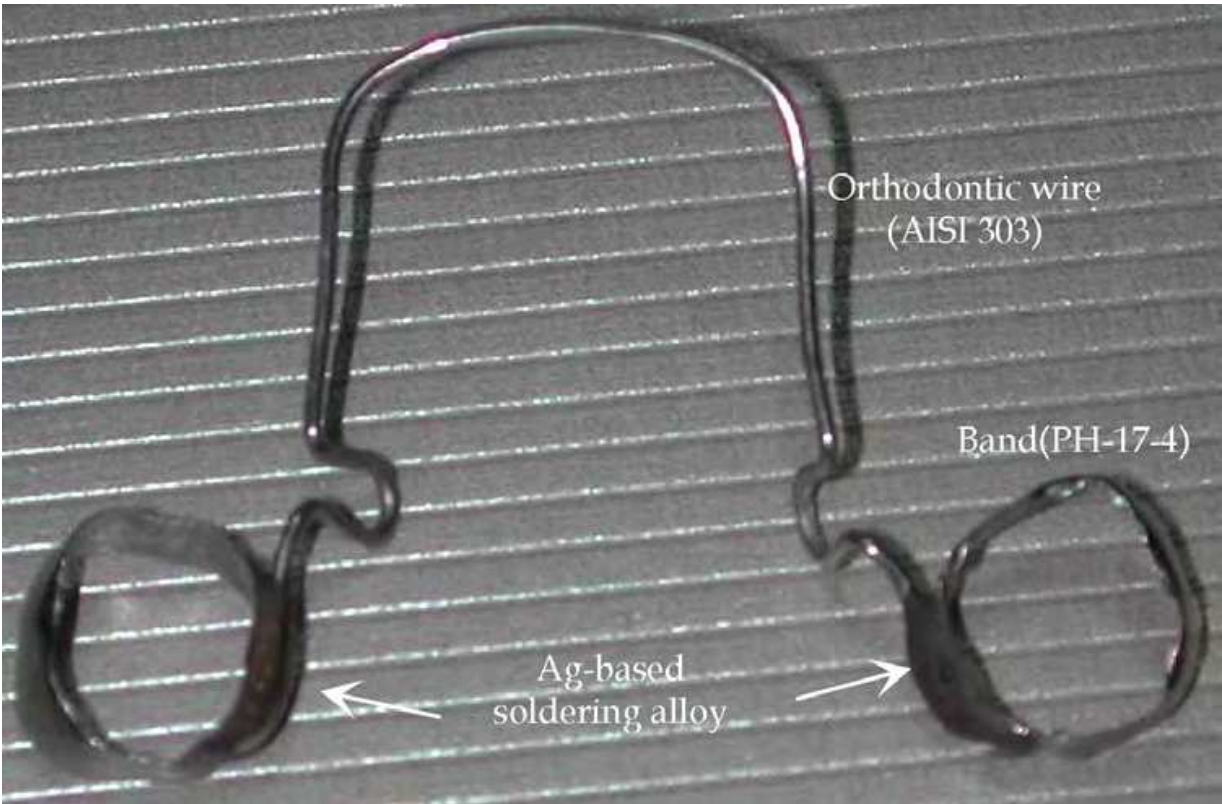


Fig. 6. An orthodontic device known as space maintainer made of two bands and a wire with two soldered joints (arrows). Bands and wires were manufactured from stainless steel whereas the soldering alloy is Ag-based alloy containing Cu, Zn and Sn.

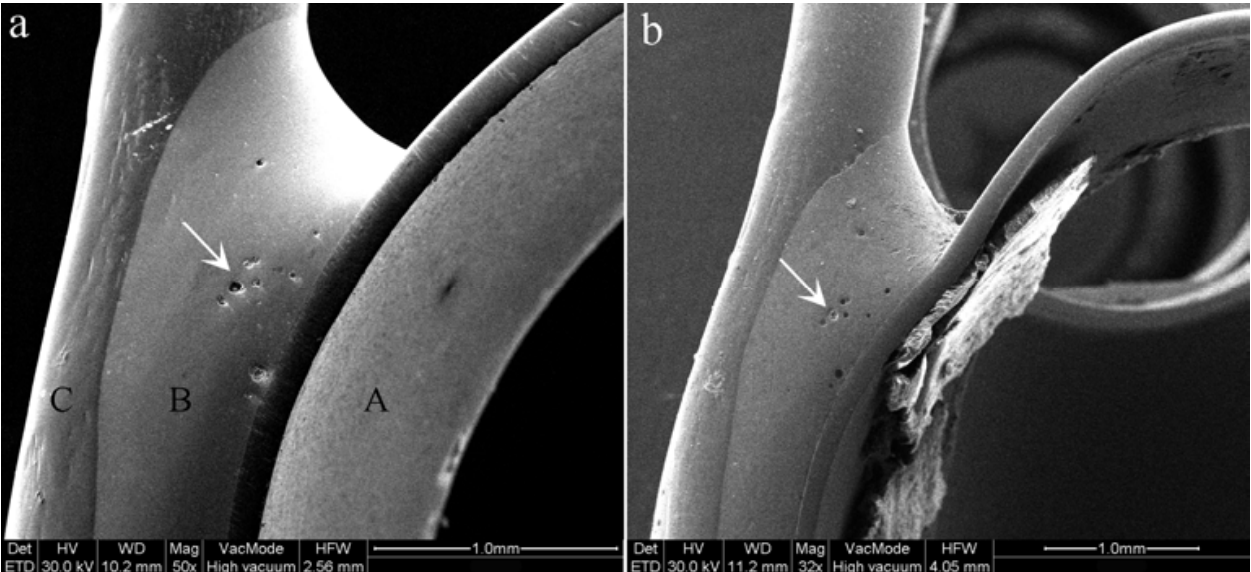


Fig. 7. Secondary Electron Images (SEI) of a joint area between the stainless steel band (A) and the orthodontic wire (C) soldered with Ag-based soldering alloy (B). (a) As-received appliance from the dental laboratory and before it was placed in the patient’s mouth. (b) The retrieved appliance from the patient’s mouth after it serviced for approximately 14 months of treatment period. External surface porosities (arrows) were used as a reference for locating exact area used for x-ray EDS analysis.

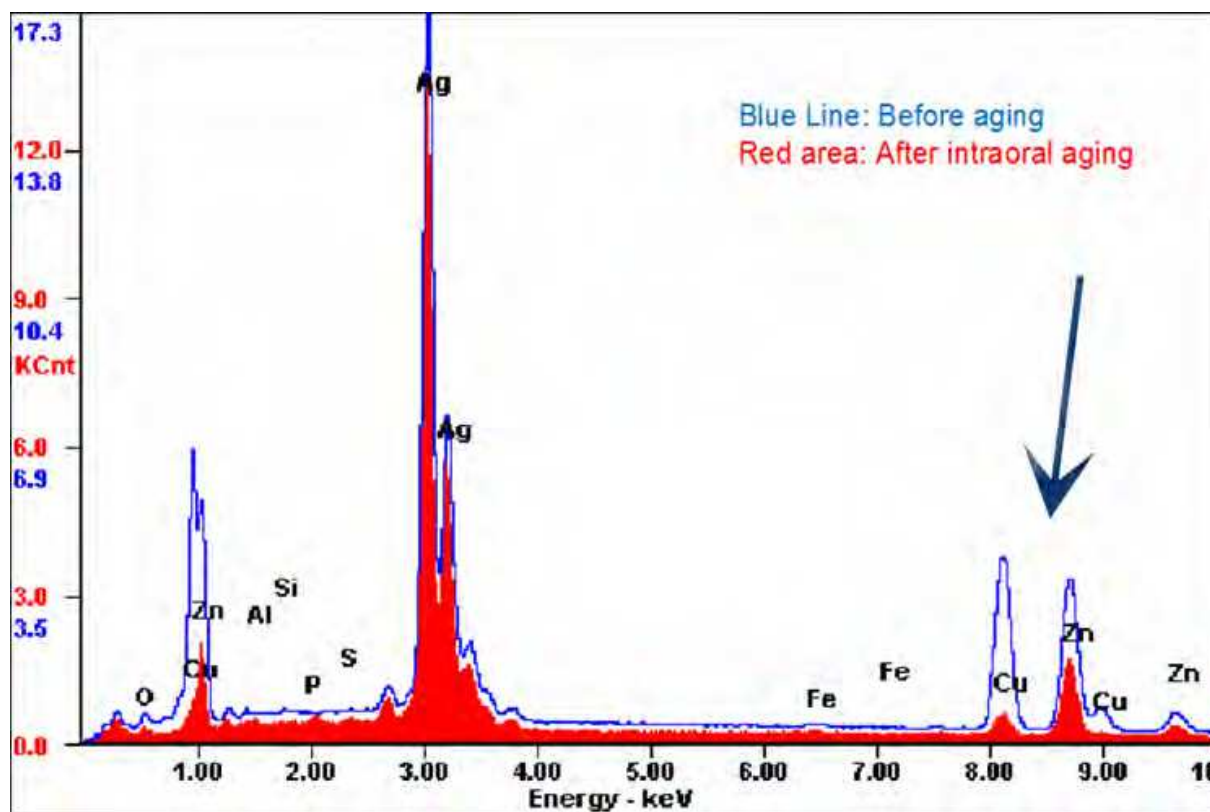


Fig. 8. EDS x-ray spectrum for the Ag-based alloy solder before and after intraoral aging. Note the decrease in Cu, Zn after long-term use *in vivo*.

Figures 8 and 9 provide additional information regarding the surface structure of the Ag-based soldering alloy. Both figures confirm that the significant decreases in Cu and Zn are appended to the dissolution of the low atomic contrast second phase, which is enriched in Cu and Zn. A possible explanation is that dental biomaterials with multiple phase structures might be prone to galvanic corrosion. Of course, the presence of the stainless steel bands and wire might have an additional effect on this phenomenon. However, this is only an assumption and the verification of galvanic corrosion requires further extended research. The important contribution of this NDT and X-ray EDS analysis is significant because it confirms other previous findings that Ag-based alloys are prone to corrosion and ionic release (Grimsdottir et al. 1992; Locci et al. 2000a; Mockers et al. 2002; Staffolani et al. 1999). These findings might be a reason for mucosal irritation, which was reported in a previous study (Bishara 1995). The significant release and dissolution of Cu and Zn during intraoral aging must be taken seriously because Cu ions have toxic effects on the human body (Locci et al. 2000b; Vannet et al. 2007; Wataha et al. 2002).

4. Dental applications of NDT as non-invasive diagnostic methods

Radiographic X-rays are used routinely in dental offices to non-invasively diagnose hard dental tissue diseases or to detect dental caries (tooth decay). However, in recent years, new technologies have been developed and introduced into the dental field for use as non-invasive diagnostic tools. The best two examples are RFA (Meredith et al. 1997) and fluorescence measurements (Jablonski-Momeni et al. 2011; Lussi et al. 2003; Rodrigues et al. 2010).

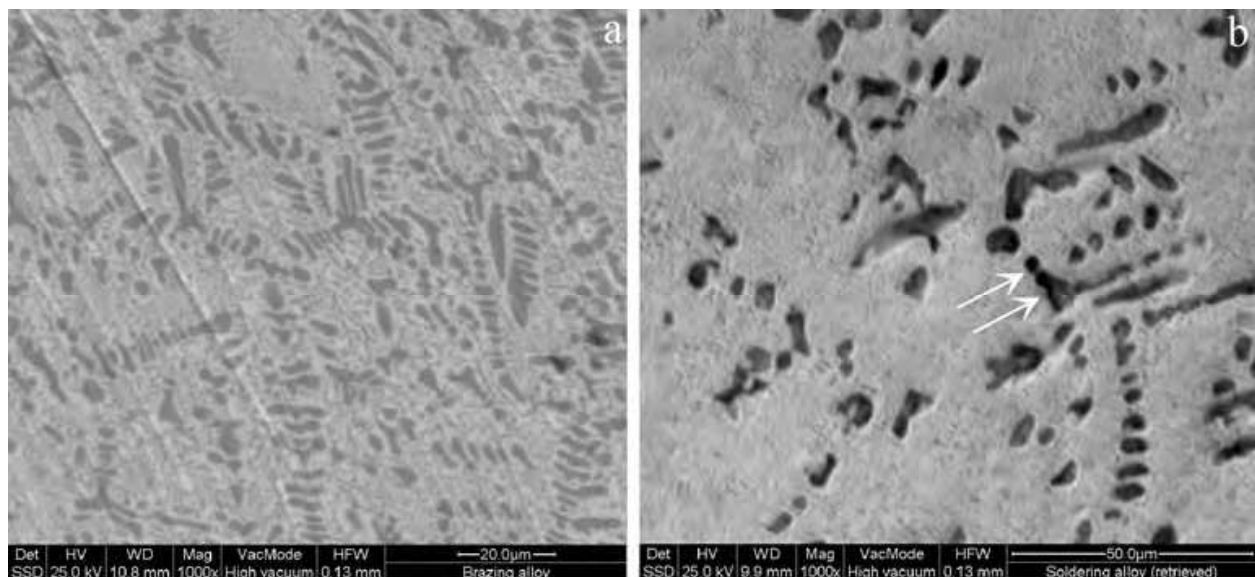


Fig. 9. Backscattered Electron Images after etching of Ag-based alloy solder before (a) and after (b) intraoral aging. The Ag based alloy has two different microstructure phases with dispersion of lower atomic contrast phase in the matrix. This second phase has been completely diluted leaving behind a random distribution of surface craters. (Original magnification: 1000X).

4.1 RFA

The main dental application of RFA as a diagnostic method is to quantify dental implant stability after surgical implant placement in the human jaw bone. Normally, when dental implants are placed in healthy human jaws, they will form and establish strong stable bond with the surrounding bone tissues after a period of several months and this phenomenon is known as *Osseointegration* (Albrektsson et al. 1986). It has been suggested in several studies that the stiffness of the bone-implant interface can be assessed by RFA (Valderrama et al. 2007; Sakoh J et al. 2006; Alsaadi G et al. 2007). Therefore, clinicians have been advised to utilize RFA to determine the strength and adequacy of the established bond (Osseointegration) before they restore implants with dental prostheses. A commonly used device for this purpose is the Osstell Mentor device (Integration Diagnostics, Goteborg, Sweden) (Figure 10a). As shown in Figure 10, part of the Osstell Mentor device comprises L-shaped transducers. These transducers will record all the information as an implant stability quotient (ISQ), which is a function of the bone-implant stiffness ($N/\mu m$) and the marginal bone height. The ISQ is a dimensionless quantity, and larger values indicate greater levels of interfacial bone-implant stiffness (meaning a higher established osseointegration with greater stability).

Besides the aforementioned beneficial diagnostic applications of RFA, it has been utilized extensively in research studies. Traditionally, research studies have evaluated the established bond between an implant and bone by histomorphometric tests. However, the main disadvantage of these tests is that they are destructive (Meredith N. 1998). Therefore, it has been suggested that RFA can be used periodically to evaluate the established bond (osseointegration occurrence) between an implant and bone without sacrificing the object in an *in vivo* study (Figure 10b) (Meredith N. 1998; Huang HM. et al. 2003).

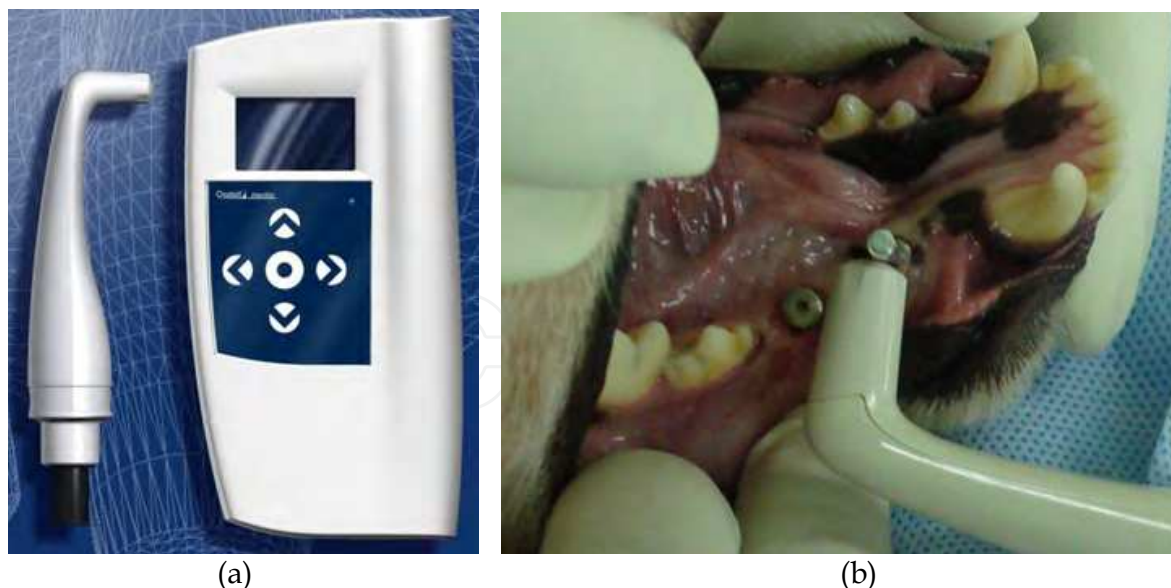


Fig. 10. (a) The Osstell device utilized normally for RFA. (b) Illustrating conduction of RFA in an animal study. It is important that the transducer be placed in same position each time a measurement is taken for a specific dental implant. Different ISQ values could be obtained by positioning the transducer in different directions.

4.2 Fluorescence measurements

Dental caries are also known as tooth decay and result from demineralization of inorganic components of the outer layer (enamel) of the tooth structure. Released bacterial lactic acid will normally lead to tooth enamel demineralization. Detection of tooth caries at early stages is crucial because it only requires a non-costly simple treatment. However, the early stages of dental caries may not be easily detected by the naked eye during routine dental examinations. Therefore, fluorescence measurements have been recommended for early detection and diagnosis of enamel demineralization (Jablonski-Momeni et al. 2011; Lussi et al. 2003; Rodrigues et al. 2010). The structure of healthy and sound tooth enamel is characterized by a low baseline fluorescence level, while demineralized and infected enamel will have an increased fluorescence level. In addition, the fluorescence level increases as the caries process advances (Lussi et al. 2001). A recently developed device for detecting dental caries at its early stages based on fluorescence measurements is the DIAGNOdent device (KaVo, Biberach, Germany). The DIAGNOdent device emits red light at 655 nm and detects bacterial metabolites in the demineralized tooth structure (Lussi et al. 2003; Lussi et al. 2006a; Lussi et al. 2006b). The DIAGNOdent device then classifies the tested regions according to the calibrated fluorescence intensity as follows: scores 0–13 = no caries, scores 14–20 = early (incipient) enamel caries and scores above 20 = advanced dentine caries (Figure 10a) (Lussi & Hellwig 2006b).

Another recently developed fluorescence camera, VistaProof (Dürr Dental, Bietigheim-Bissingen, Germany), is used for early diagnosis of dental caries. The VistaProof emits blue light at 405 nm (Jablonski-Momeni et al. 2011) and records fluorescence from the probed tooth surfaces in the form of digital images (Rodrigues et al. 2008). Intact tooth structures show green fluorescent images, while infected and demineralized tooth structures show

blue-violet fluorescent images. Infected areas with increased numbers of bacteria and bacterial byproducts show red fluorescent images (Figure 11b). The digital software utilized by the VistaProof quantifies the color components and provides scoring outcomes ranging from 0–4 that indicate the penetration depth of the dental caries within the tooth structure (Figure 11b). The scoring outcomes are good diagnostic values for the presence or absence and the severity of dental caries. The values are used as follows: 0–0.9 = sound and healthy tooth structure; 0.9–1.5 = initial (incipient) enamel caries; 1.5–2.0 = deep enamel caries; 2.0–2.5 = dentine caries; and above 2.5 = deep dentine caries. It is important to mention that, despite the reported reliable applications of the DIAGOdent and VistaProof for non-invasive diagnosis of dental caries, dentists routinely verify their findings by taking radiographic X-rays to diagnose the occurrence of dental caries.

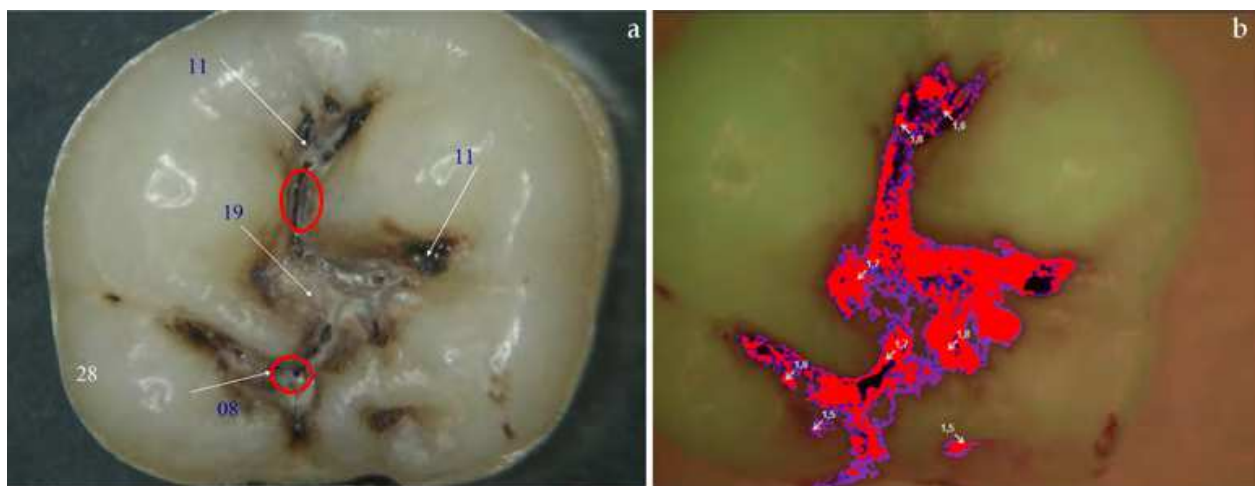


Fig. 11. Occlusal surface of a molar tooth with dental caries. The infected areas were diagnosed by DIAGNOdent (a) and VistaProof (b). Numbers in both images provide valuable information regarding the extent and penetration depth of dental caries within the tooth structure.

5. Conclusions

NDT plays very important roles in dentistry, and in the dental biomaterials research field in particular. However, the application of NDT on a daily basis for dental diagnosis purposes and for assuring adequate therapeutic quality is limited, mainly because of the significant increases in relevant time and cost. Luckily, NDT along with its various applications in the dental biomaterials research field is performed routinely by scientific researchers. Consequently, this NDT has led to noticeable enhancements of the quality, performance and biocompatibility of dental biomaterials that are placed daily into patients' mouths.

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7. References

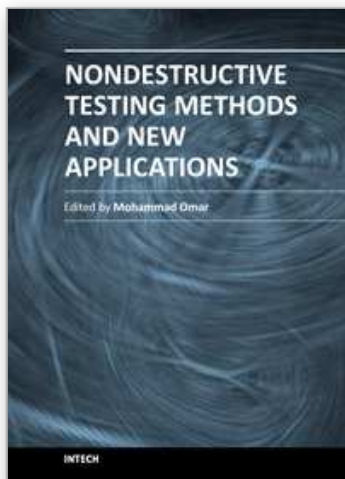
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Nondestructive testing enables scientists and engineers to evaluate the integrity of their structures and the properties of their materials or components non-intrusively, and in some instances in real-time fashion. Applying the Nondestructive techniques and modalities offers valuable savings and guarantees the quality of engineered systems and products. This technology can be employed through different modalities that include contact methods such as ultrasonic, eddy current, magnetic particles, and liquid penetrant, in addition to contact-less methods such as in thermography, radiography, and shearography. This book seeks to introduce some of the Nondestructive testing methods from its theoretical fundamentals to its specific applications. Additionally, the text contains several novel implementations of such techniques in different fields, including the assessment of civil structures (concrete) to its application in medicine.

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