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Corina Marcauteanu  
Adrian Bradu  
Cosmin Sinescu  
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Adrian Gh. Podoleanu

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Corina Marcauteanu,<sup>a</sup> Adrian Bradu,<sup>b</sup> Cosmin Sinescu,<sup>a</sup> Florin Ionel Topala,<sup>a</sup> Meda Lavinia Negrutiu,<sup>a</sup> and Adrian Gh. Podoleanu<sup>b</sup>

<sup>a</sup>Universitatea de Medicina si Farmacie "Victor Babes," Facultatea de Medicina Dentara, Timisoara 300041, Romania

<sup>b</sup>University of Kent, Applied Optics Group, School of Physical Sciences, Canterbury, Kent, CT2 7NH, United Kingdom

**Abstract.** A fast swept-source optical coherence tomography (SS-OCT) system is employed to acquire volumes of dental tissue, in order to monitor the temporal evolution of dental wear. An imaging method is developed to evaluate the volume of tissue lost in *ex vivo* artificially induced abfractions and attritions. The minimal volume (measured in air) that our system could measure is  $2352 \mu\text{m}^3$ . A volume of 25,000 A-scans is collected in 2.5 s. All these recommend the SS-OCT method as a valuable tool for dynamic evaluation of the abfraction and attrition with remarkable potential for clinical use. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JBO.19.2.021108](https://doi.org/10.1117/1.JBO.19.2.021108)]

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## 1 Introduction

Pathologic tooth wear refers to the loss of dental hard tissues that is not caused by caries or macro trauma, but by other mechanisms such as abrasion, attrition, erosion, pathological bending of teeth, etc. It affects aesthetics, function, and longevity of the remaining dental structures.

Abfractions appear in the presence of occlusal overload<sup>1,2</sup> and are due to flexure and chemical fatigue degradation of cervical dental hard tissues.<sup>3</sup> Abfractions observed in our patients are the signs of occlusal overload produced by bruxism (strong, unconscious, and rhythmic grinding and/or clenching of teeth during the day or during the sleep,<sup>3</sup> mainly caused by high levels of emotional stress) and by occlusal interferences (unwanted tooth-to-tooth contacts) during protrusive or laterotrusive mandibular movements. In bruxing patients, abfractions are often associated with pathological attrition facets.

Abfractions have a characteristic "V" shape with a sharp borderline in the occlusal/incisal intact enamel and with a glossy surface. They are located predominantly in the buccal cervical region of occlusal-overloaded teeth. The depth and the extent of the lesion area depend on the intensity, duration, direction, frequency, and location of occlusal forces.

Pathological attrition is the mechanical wear resulting from bruxism (parafunctional tooth-to-tooth contact) and is limited to the occlusal surfaces of teeth. Attrition facets of opposing teeth match in different eccentric mandibular positions.

Apart from abfractions and pathological attrition, some other mechanisms such as abrasion and erosion contribute to dental wear. Abrasion is an abnormal wearing away of the tooth substance by causes other than mastication and swallowing (tooth brushing, holding objects between the teeth or practicing a hard diet). Erosion is a progressive loss of tooth substance by chemical processes that do not involve bacterial action, often associated with dentine hypersensitivity.<sup>4</sup> All the wear mechanisms presented above generally overlap and an etiological diagnosis is mandatory, in order to choose the most appropriate treatment. Currently, the only elements to be considered for an etiological diagnosis are the medical history and the morphological appearance of the lesions. In this article, two of the wear mechanisms, attrition and abfraction, will be considered.

The evolution of the pathological dental wear over time is essential for the prognosis of teeth and for the initiation of the most suitable therapeutic steps. Monitoring involves a series of examinations and measurements that are repeated after a certain period, in order to assess whether a particular phenomenon is progressive or not. Monitoring is essential in the treatment of dental wear. This is the only way to determine if the tooth wear is active or stationary. An active wear process requires immediate therapeutic measures, which focuses on its main causes (occlusal equilibration by selective grinding, occlusal appliance, control of soda consumption, treatment of gastroesophageal reflux, correct tooth-brushing technique, etc).

Several monitoring methods of tooth wear are currently employed. One such method consists of the macroscopic clinical evaluation of grades of tooth wear severity directly in the mouth; a tooth wear index (TWI) was proposed by Smith and Knight in order to score the wear of all four visible dental surfaces (1984).<sup>5</sup> However, the TWI is not accurate in terms of quantity.<sup>4</sup>

Another monitoring method of tooth wear applied the TWI on study casts.<sup>6</sup> The consecutive casts were taken at two time

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Address all correspondence to: Cosmin Sinescu, Universitatea de Medicina si Farmacie "Victor Babes," Facultatea de Medicina Dentara, Timisoara, Romania. Tel: +40722280132; Fax: +40256220479; E-mail: [minosi-nescu@yahoo.com](mailto:minosi-nescu@yahoo.com); and Meda Lavinia Negrutiu, Universitatea de Medicina si Farmacie "Victor Babes," Facultatea de Medicina Dentara, Timisoara, Romania. Tel: +40745166620; Fax: +40256220479; E-mail: [meda\\_negrutiu@yahoo.com](mailto:meda_negrutiu@yahoo.com)

intervals (at the time of the first presentation of the patient and after 14 to 50 months) and were used to evaluate the progression of tooth wear by means of the TWI. Unfortunately, compliance of patients and dentists in taking and keeping casts was poor;<sup>7</sup> this method also has limitations imposed by the accuracy and the dimensional changes of the impression materials used to manufacture the study casts (greater than the magnitude of tooth wear over short periods).<sup>4</sup>

Due to the lack of a reliable technique to monitor and to measure the wear, there are very few quantitative studies on the progression of dental wear. To improve on the quantitation, Bartlett et al.<sup>8</sup> measured the amount of erosion on the palatal surfaces of central incisor teeth. Metal disks were cemented to the tooth surface and impressions were taken at 6-months intervals. Wear was estimated by scanning the impressions with a contact laser profilometer. This was used to measure the changes in depth, due to wear around the disk over a 6-month period using fixed reference points on the metal disks. A mean wear of 36.5  $\mu\text{m}$  (range 17.6 to 108.2  $\mu\text{m}$ ) in 6 months was reported for patients with erosion and a median of 3.7  $\mu\text{m}$  (range 0.5 to 15.8  $\mu\text{m}$ ) for controls. Pintado et al.<sup>9</sup> investigated occlusal attrition in a group of 18 young adults and found a steady wear rate of 0.04 mm<sup>3</sup> per year by volume and 10.7  $\mu\text{m}$  per year by depth, averaged over all teeth over 2 consecutive years. Pintado et al.<sup>10</sup> also measured the size of noncarious cervical lesions and the occlusal wear in one patient over a 14-year period. Surfaces of epoxy replicas were digitized with a contact digitizing system. Sequential digitized surfaces were fit together and analyzed using the AnSur-NT surface analysis software. A direct correlation between occlusal wear and increase of no-cariou cervical lesions was found. The volume loss and the mean depth of three cervical lesions in the lower first and second premolars and the lower first molar were measured. The mean annual increase in depth of the noncarious cervical lesions was in the order of 30  $\mu\text{m}/\text{year}$  for the premolar lesions and in the order of 55  $\mu\text{m}/\text{year}$  for the molar lesion. However, all studies<sup>8-10</sup> presented above were performed *ex vivo* on models obtained through impression procedures.

We previously demonstrated that optical coherence tomography (OCT) is a promising, noninvasive alternative technique for the early detection and monitoring of occlusal overload in bruxing patients.<sup>11-13</sup> Time domain (TD)-OCT and fluorescence microscopy (FM) were used to investigate the wear of anterior teeth derived from young patients with light, active bruxism.<sup>11</sup> The teeth presented first-degree pathological wear (TWI score equal to 1). The combination of information collected by OCT and FM revealed a characteristic pattern of enamel cracks that reached the tooth surface.

Also, TD-OCT was used to investigate extracted anterior teeth with a normal crown morphology (without pathological attrition), which is derived from patients with active first-degree bruxism and from subjects without parafunction.<sup>12</sup> The teeth from nonbruxing patients revealed a homogenous structure of the superficial enamel on the TD-OCT images. Despite the normal crown morphology, the teeth extracted from patients with first-degree bruxism showed signs of enamel damage on the TD-OCT images. This consisted of a characteristic pattern of cracks, which did not reach the tooth surface.

Our research team also demonstrated microstructural characterization of abfractions by TD-OCT.<sup>13</sup> The TD-OCT investigation of bicuspid with normal crown morphology revealed a homogenous structure of the buccal cervical enamel. Imaging of occlusal-

overloaded bicuspid (derived from patients with active bruxism) in two regimes was used, en-face, which produced constant depth OCT images (C-scans) and cross-sectioning and obtain cross-section OCT images (B-scans). These images revealed the wedge-shape loss of cervical enamel and the damage of the underlying dentin. The high-occlusal forces produced a characteristic pattern of large cracks, which reached the tooth surface.

OCT has advanced considerably since it was first applied to the eye imaging. At the time of introduction, TD-OCT imaging systems were able to produce *in vivo* optical cross-sections of the samples at typical axial resolution of tens of micrometers and acquisition speeds as low as a couple of images per second (a few hundred of A-scans/s). When the focus and the transversal resolution are not important, TD-OCT can be replaced by Fourier domain methods, which is much faster and gives better sensitivity. For *in vivo* investigations, a fast-imaging system is necessary.

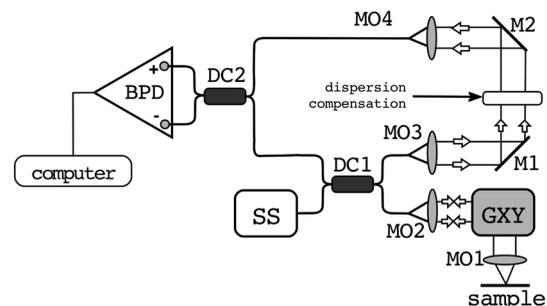
In this article, we demonstrate that a swept-source OCT (SS-OCT) system has the potential to be used as a tool to monitor the evolution of pathological dental wear.

## 2 Materials and Methods

A number of five mandibular premolars and five mandibular incisors were used for this study. They were carious-free and all extracted for orthodontic reasons. On all these teeth, in order to simulate the apparition and evolution of the abfraction (for premolars) and attrition (for incisors), four levels of artificial defects similar to those observed in the clinic were created. The TWI proposed by Smith and Knight<sup>5</sup> was employed to score the artificial vestibular abfractions namely for: (1) minimal loss of contour and (2) cervical defect less than 1-mm depth. Artificially, incisal attritions exhibited a depth corresponding to a TWI of 1, namely for loss of enamel surface characteristics without exposing the dentine.

After every level of induced defect to the tooth, OCT scanning was performed. B-scans were acquired, and three-dimensional (3-D) reconstructions were generated.

An SS-OCT instrument is used in this study, as depicted in Fig. 1. The SS is from Axsun Technologies Ltd., Billerica, Massachusetts (1060-nm swept laser engine) having a central wavelength of 1050 nm, a sweeping range of 106 nm (measured at 10 dB), an average output power of 16 mW, and a sweeping rate of 100 kHz. A depth resolution determined by the SS of 12  $\mu\text{m}$  in air was experimentally measured. Light from SS is split into a sample arm and a reference arm by the directional coupler DC1. In the sample arm, to convey light to and from the object, a pair of orthogonal galvo-scanner mirrors (GXY) is



**Fig. 1** Anatomy of the swept-source optical coherence tomography (SS-OCT) instrument. SS: swept-source; DC1, 2: directional couplers; MO1-4: microscope objectives; M1, 2: flat mirrors; GXY: pair of galvo-scanner mirrors; BPD: balanced photodetector.

used. The combination of two microscope objectives (MO1 and 2) determines a lateral resolution of  $\sim 14 \mu\text{m}$ . The optical power on the sample is 3.6 mW. In the reference arm, light is directed via the microscope objectives MO3, 4 and the flat mirrors M1, 2 toward the directional coupler DC2, where it interferes with light originating from the sample. The DC2 output signals are sent to a balance photodetector BPD (Thorlabs, Newton, New Jersey, model PDB460C, bandwidth of 200 MHz). The output of the photodetector is digitized by a 12-bit analog-to-digital acquisition card (Alazartech ATS9350, Montreal, Canada), while an "in-house" Labview (National Instruments, Austin, Texas) created software is used to produce, display, and record the images. The lateral size of the 3-D images, determined by the amplitude of the voltages applied to the galvo-scanners and the focal length of MO1, is  $4.4 \times 4.4 \text{ mm}$ , while their axial size, determined by SS, is 3.7 mm (measured at 6 dB). The system is able to produce  $500 \times 640$  pixels B-scan images (cross-sectional images of the sample) at a frame rate of 100 Hz. 3-D reconstructed images could then be produced, which are of  $500 \times 500 \times 640$  (pixels). Inspection of the volume can be performed either along B-scans or C-scans.

As 500 A-scans are used to construct each B-scan image, given the sweeping speed of the SS, a number of

100 B-scans/s are acquired per second. Hence, in order to acquire data to reconstruct a 3-D volume made of 500 B-scans, 2.5 s are needed.

The sensitivity of the system was measured by first adjusting the reference arm signal, such that the intensity at the photodetectors was near to their saturation value. Then, a neutral density filter, characterized by an optical density  $\text{OD} = 2$ , was placed into the sample arm. The sensitivity at a particular depth  $z$  was calculated using the following equations, according to similar procedures described in Refs. 14 and 15.

$$\text{Sensitivity}(z) = 40 + 20 \cdot \log \left[ \frac{\text{Amplitude FFT signal}(z)}{\text{Amplitude noise floor measured outside } z} \right] \quad (1)$$

The number 40 is due to the neutral density filter. As it can be seen in Fig. 2, a sensitivity drop-off of around 6 dB over the whole longitudinal size of the images can be achieved.

### 3 Results

The artificially induced defects are similar to those observed in the clinic (scored by the TWI). The loss of dental hard tissue is qualitatively observed on the B-scans as two-dimensional (2-D) images and 3-D reconstructions (volumes).

The B-scan images (Fig. 3) allow the evaluation of the maximum progression of the abfraction inside the tooth: 0.37 mm [Fig. 3(b)]; 0.52 mm [Fig. 3(c)]; 0.68 mm [Fig. 3(d)], and 0.92 mm [Fig. 3(e)]. The different depths can be easily visualized employing a color chart [Fig. 3(f)]. The progression of the abfraction inside the cervical volume of the tooth is important. The color chart can easily be used to monitor the abfraction and to explain the phenomenon to the patient.

For the attritions, the evaluation of the depth dynamics using OCT permits the identification of the maximum distance between the initial incisal edge of the incisor and the enamel affected by attrition: 0.25 mm [Fig. 4(b)]; 0.42 mm [Fig. 4(c)]; 0.58 mm [Fig. 4(d)], and 0.83 mm [Fig. 4(e)]. The color chart fully describes the dynamics of the attrition evolution.

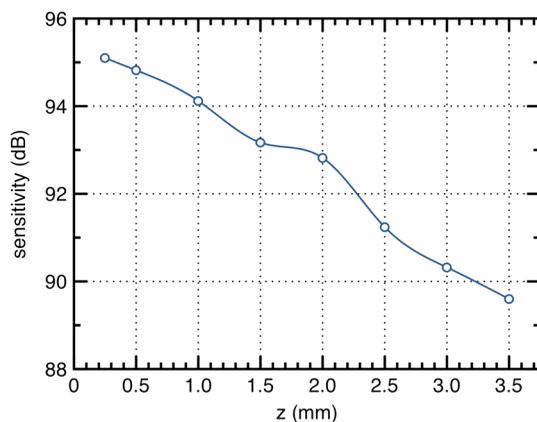


Fig. 2 Sensitivity drop-off versus depth of the SS-OCT imaging system.

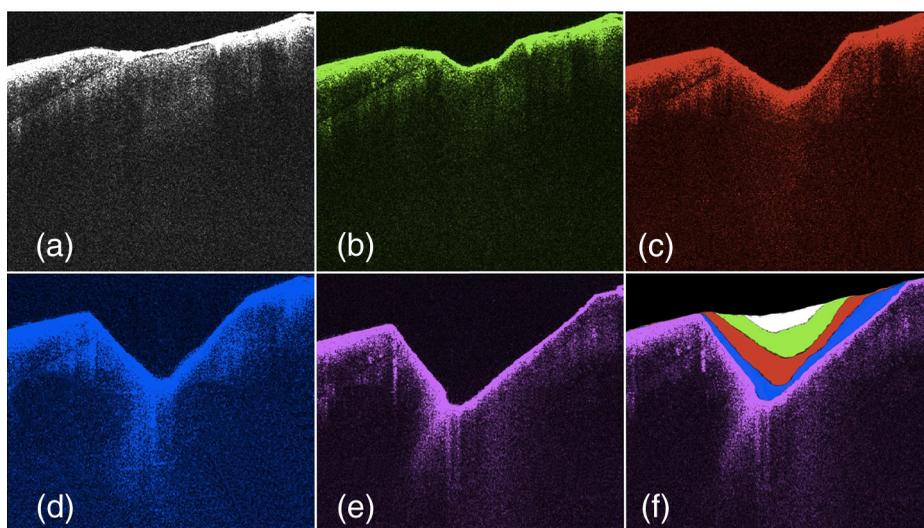
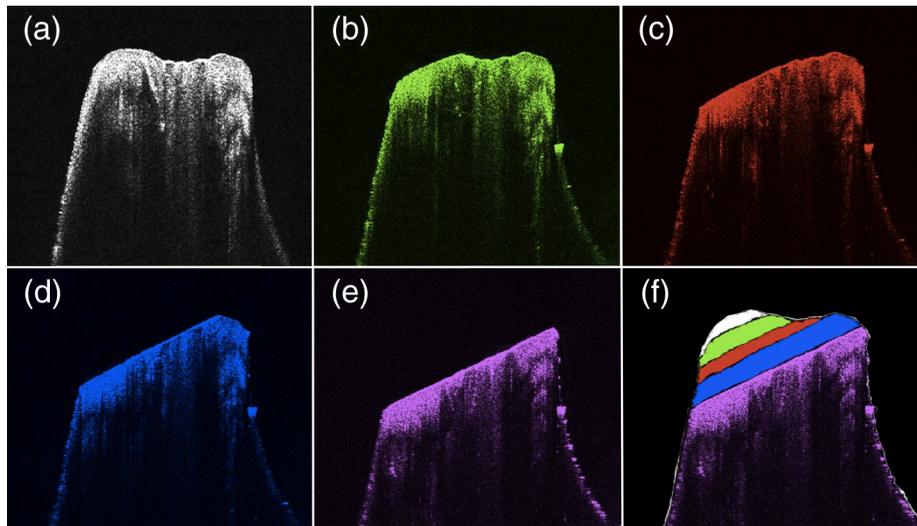


Fig. 3 B-scan OCT images illustrating abfractions on the premolar cervical region of sample 3; (a) no defect; (b–e) different levels of defects; (f) the amount of lost hard tissue presented successively. The size of the B-scan images is 3.2 mm (lateral)  $\times$  2.7 mm (depth measured in air).



**Fig. 4** B-scan OCT images illustrating pathological attritions on the incisal regions of the incisors, sample 4; (a) no initial defect; (b–e) different levels of defects; (f) the amount of lost hard tissue presented successively. The size of the B-scan images is 3.2 mm (lateral)  $\times$  2.7 mm (depth measured in air).

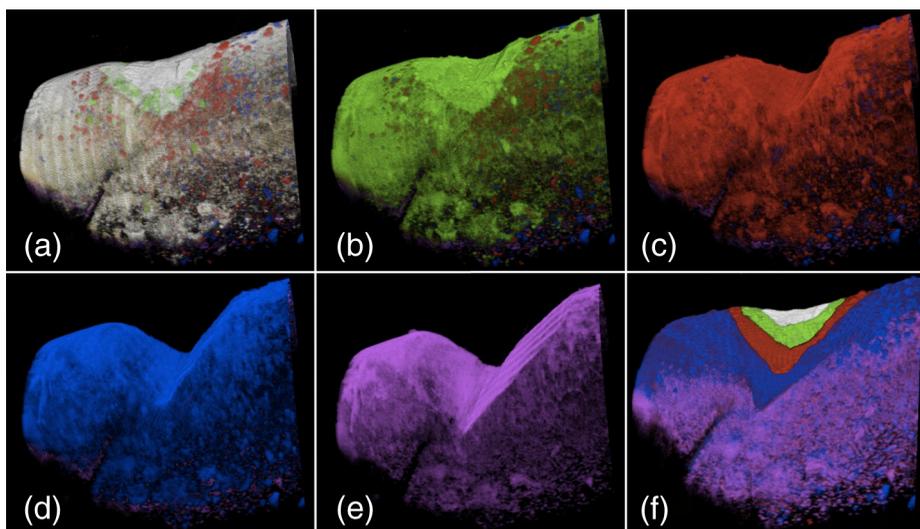
Attrition is considered as a physiological process (caused by mastication), if the wear rate is approximately  $10.7 \mu\text{m}/\text{year}$ .<sup>9</sup> Based on the data of Cunha-Cruz et al.,<sup>16</sup> pathological attrition (moderate to severe wear facets) can be defined as the loss of 1 mm or more for the tooth structure. Under normal conditions (at a rate of about  $10.7 \mu\text{m}/\text{year}$ ), 1 mm is lost in about 90 years. However, not all patients present moderate to severe pathological attrition. Some of them show incipient wear facets with a dental hard tissue loss less than 1 mm, but exceeding the physiological wear rate of  $10.7 \mu\text{m}/\text{year}$ . Therefore, the evolution of attrition will always be assessed according to the patient's age. Our measured values for the loss of dental hard tissues on the incisal surface of mandibular incisors (0.25, 0.42, 0.58, and 0.83 mm) correspond to incipient pathological attrition in patients aged over 20 years. On the other hand, abfractions are always a sign of pathology, being produced by occlusal overload. Our results approximately reproduce the evolution of these

cervical lesions, which would happen over periods of 5 to 8 years (at a wear rate of  $30 \mu\text{m}/\text{year}$ ).<sup>10</sup>

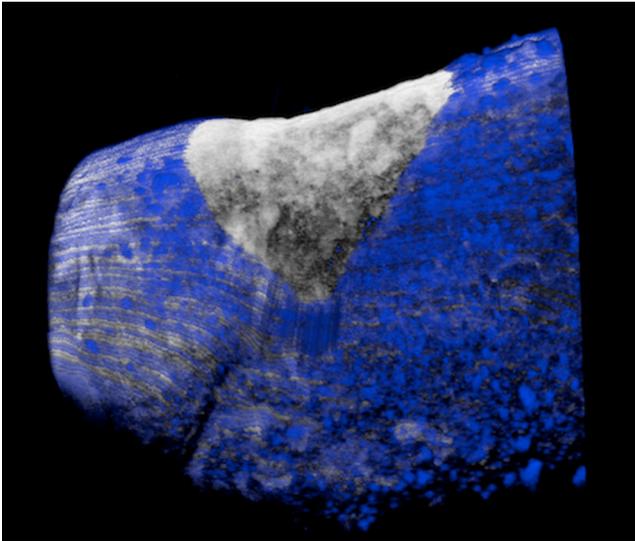
The quality assessment of the dynamic evolution of the artificially induced abfractions and attritions is extremely important for devising the most appropriate clinical procedure. This may offer information about the speed of the defect evolution, and thus, may serve to choose the most suitable therapeutic procedure needed. Also, the patient can better understand the dynamic of the process and can more readily accept the necessity of a specific treatment.

Nevertheless, a quantitative volumes approach is needed in order to better evaluate the speed of the defect progression. Different authors<sup>8–10,16</sup> presented mean values of the maximum depth of the dental defect. More useful for the clinician would be a quantitative imagistic presentation for the volume of the loss of dental tissue.

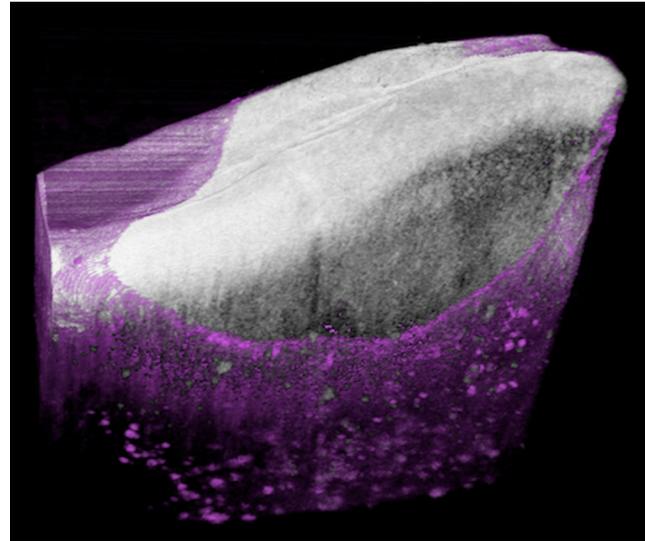
For this purpose, quantitative evaluation of the amount of lost hard tissue was performed for each attrition level.



**Fig. 5** Three-dimensional (3-D) reconstructions of the vestibular cervical areas of the premolar sample 3, where the abfractions usually appear: (a) the initial area with no modification; (b–e) after different levels of abfraction evolution; (f) the 3-D amount of the lost hard tissue presented cumulatively. The size of the volumes is 3.2 mm  $\times$  3.2 mm (lateral)  $\times$  2.7 mm (depth measured in air).



**Fig. 6** 3-D aspect of the final total amount of the lost hard tissue due to the induced abfraction evolution in a premolar (sample 3). The size of the volume is 3.2 mm × 3.2 mm (lateral) × 2.7 mm (depth measured in air).



**Fig. 8** 3-D aspect of the final total amount of the lost hard tissue (white regions) due to the induced attrition evolution in incisors (sample 4). The size of the volume is 3.2 mm × 3.2 mm (lateral) × 2.7 mm (depth measured in air).

The minimum detectable change in the volume of the sample by the OCT system used in this study is  $\sim 2352 \mu\text{m}^3$ .

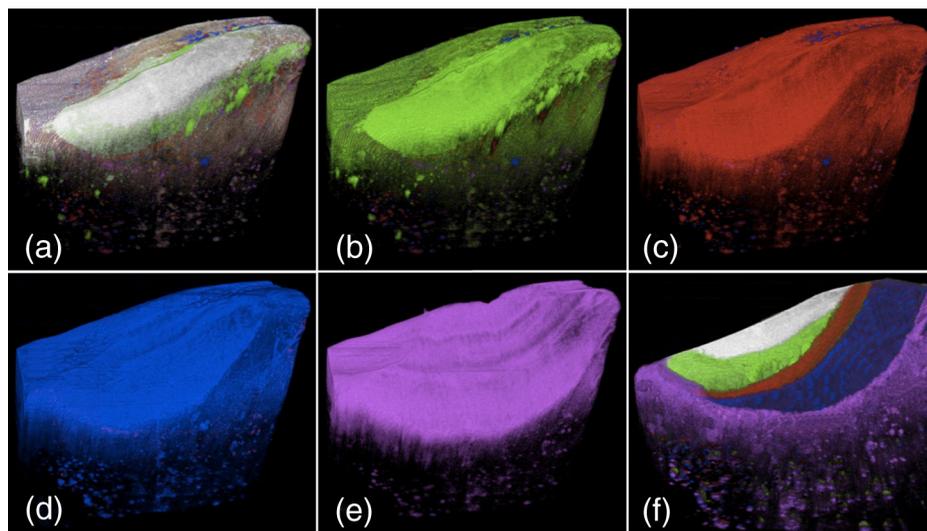
When the 3-D reconstruction was considered, the maximum depths of the abfractions were higher than the values measured on the B-scan images: 0.41 mm [Fig. 5(b)]; 0.74 mm [Fig. 5(c)]; 0.98 mm [Fig. 5(d)], and 1.173 mm [Fig. 5(e)].

For quantitative evaluations of volumes, the Image J software was employed. The B-scans files were used for both abfraction and attrition evaluations. Stacks of B-scan images corresponding to various levels of defects were collected. The volume difference between the stack corresponding to the initial situation (no defect) and the stacks corresponding to each level of artificial defect were then performed. In this way, the value of the area corresponding to the amount of the lost tissue was obtained and evaluated in the same software (Image J). By calculating the

areas of the amount of lost tissue corresponding to each of the different B-scans, the final volumes of the lost hard tissue were obtained:  $0.1112 \text{ mm}^3$  for the first-level defect [Fig. 5(b)],  $0.561 \text{ mm}^3$  for the second-level defect [Fig. 5(c)],  $1.230 \text{ mm}^3$  for the third-level defect [Fig. 5(d)], and  $2.524 \text{ mm}^3$  for the fourth-level defect [Figs. 5(e) and 6].

Using the 3-D reconstructions of the attritions, the maximum depth values obtained were different from the values measured on the B-scan images: 0.33 mm [Fig. 7(b)]; 0.67 mm [Fig. 7(c)]; 0.83 mm [Fig. 7(d)], and 1.083 mm [Fig. 7(e)].

For the incisal attritions, the calculated defect volumes were:  $0.125 \text{ mm}^3$  for the first-level defect [Fig. 7(b)],  $0.431 \text{ mm}^3$  for the second-level defect [Fig. 7(c)],  $0.714 \text{ mm}^3$  for the third-level defect [Fig. 7(d)], and  $1.980 \text{ mm}^3$  for the fourth-level defect [Figs. 7(e) and 8].



**Fig. 7** 3-D reconstructions of the incisal parts of the incisors where the attrition was induced, sample 4; (a) the initial volume with no modification; (b–e) after different levels of attrition evolution; (f) the 3-D amount of the lost hard tissue presented successively. The size of the volumes is 3.2 mm × 3.2 mm (lateral) × 2.7 mm (depth measured in air).

The total amount of the hard dental tissue lost as well as the evolution of such loss are important. Providing these two pieces of information constitutes a useful guidance for the clinical evaluation of the abfraction and attrition.

A major advantage of this technology is provided by the speed of acquisition, more than 100 times faster than the TD-OCT used in our previous studies.<sup>11–13</sup> The method is equally applicable on faster systems working at over 1-MHz line rate.<sup>17,18</sup> A high-speed SS-OCT may prove a suitable clinical tool for dentistry.

One of the most important features of this study was to demonstrate that the OCT technology could be used by clinicians to evaluate the abfractions and attrition in real time, as a first step before being extended to *in vivo* applications. Additionally, this imaging method can also reveal the damage of the underlying dentine in teeth affected by forms of pathological wear. Our previous studies demonstrated a characteristic pattern of cracks in the dentine of the affected teeth.<sup>11–13</sup>

#### 4 Conclusion

A fast OCT system was employed to acquire volumes of dental tissue. An imaging method was developed to evaluate the volume of tissue lost. This method can be used as a valuable tool in the evaluation of the dynamic evolution of *ex vivo* artificially induced abfractions and attritions. OCT is an imaging method that is able to measure minute changes in the tooth morphology, having the potential to be employed as an effective tool for monitoring the temporal evolution of dental wear. The experiment with extracted teeth presented is a preliminary necessary step before designing a hand-held probe for *in vivo* investigations. This preliminary step allowed us to demonstrate that the SS-OCT system is capable of assessing the minimum volumes of hard dental tissue lost (abfractions and attritions). By further developments of hand-held probes, OCT can offer the possibility of providing *in vivo* volumetric measurements and identification of fractural lines in dentine. These capabilities are unique for OCT instrumentation. The 2-D and 3-D pictures prove the OCT ability in the evaluation of dental abfractions and attritions. Our system could measure a minimal volume of  $2352 \mu\text{m}^3$ , where each volume is acquired as 25,000 A-scans in 2.5 s. All these recommend the SS-OCT method as a valuable tool for dynamic evaluation of the abfraction and attrition with remarkable potential for clinical use.

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