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## Buonocore Memorial Lecture

# Operative Dentistry and the Abuse of Dental Hard Tissues: Confocal Microscopical Imaging of Cutting

*Michael Buonocore*

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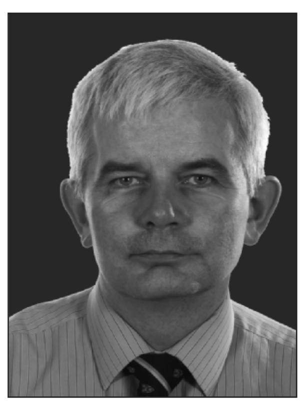

*Timothy Frederick Watson*

### SUMMARY

**We reviewed studies wherein the cutting of dental tissues, simulating interactions that would occur under clinical circumstances in the mouth, have been observed directly–*first* by real time, video rate, stereoscopic, three-dimensional scanning electron microscopy; and *second and more conveniently*, by video rate confocal optical microscopy. We have observed, directly, both the interactions of slow-moving cutting instruments emulating "chisels" and high-speed**

**events, including the effects of rotary burs and air-propelled abrasive particles and soft powder slurries. The observational data contribute to our basic understanding of the functional behavior of dental tissues and formed a useful background for the practitioner of operative dentistry.**

## INTRODUCTION

Almost by definition, "operative dentistry" implies some form of modification to the tissues that form the teeth. Hundreds of thousands of dentists around the world spend a good deal of their time using instruments to mechanically prepare cavities within these hard tissues so that they can be restored with suitable filling materials. Sometimes, there is little preparation required, and the originator of this eponymous lecture, Michael Buonocore, was one of the first people to realize that crude, mechanistic approaches to restoration retention were not going to be essential if adhesive techniques were employed.[1] Indeed, Buonocore is credited with being the inventor of dental acid etching as a means of improving the retention of resins to tooth tissue.

Despite this, the use of enamel acid etching actually evolved in North America at least 51 million years prior, with the *Perissodactyla* (for example, *Hyracotherium*: an early horse), whose high-crowned teeth had enamel covered in cementum: the same arrangement persists in modern equids. It allows both a periodontal attachment to the long crown, which has to function long before an anatomical root is formed, and attachment of the packing and binding cementum, which joins the parts of the crown together at the (future) occlusal surface. The attachment of cementum is aided by surface roughening of the enamel, achieved with an osteoclast-based etching process after the ameloblasts obligingly move off the scene after completion of the maturation phase of amelogenesis.[2-3] The same phenomenon or resorption-formation coupling of (a bone-like tissue) cementum to enamel also occurs piecemeal during the later stages of resorption of human deciduous teeth.[4]

However, with the ravages of caries, tooth wear and trauma, the need for some form of mechanical preparation often arises. Again, one would consider that this a relatively modern phenomenon, but recent work has shown that the first interventional dental procedures date back to between 7500–9000 years ago.[5] In these individuals, cavities were cut into the occlusal surfaces of molars using flint instruments, although the reason for their prescription is lost in the midst of time. It may appear somewhat primitive to be using flint to cut cavities, but we are not that much more advanced by using diamond burs in our turbines today.

Continuing with our brief review of dental hard tissues and palaeontology, the beauty of enamel is that the

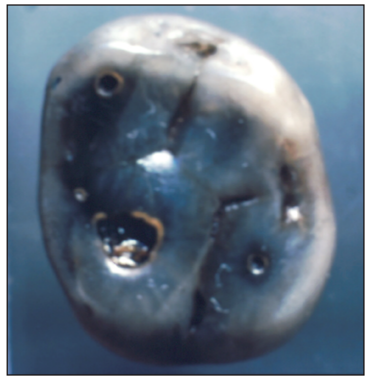

Figure 1. *Worn* Australopithecine *hominid tooth occlusal surface 1-2 million years old.*

Figure 2. *Reflection confocal image of enamel prisms from* Australopithecus Boiseii *tooth. Tandem scanning confocal microscope. TSM x 100/1.4 Numerical aperture (NA) oil immersion objective Fieldwidth 90 µm.*

cellular mechanisms that contribute to its construction are fossilized within the hard tissue structure as the developing tooth mineralizes: a very useful feature for researchers in this field. As an example, the heavily worn fossil tooth from an *Australopithecine* hominid of 1-2 million years ago (Figures 1 and 2) would be indistinguishable in microscopic structure from a recently extracted, heavily worn tooth when imaged using a confocal optical microscope. The existence of the boundary discontinuities within enamel that partly define the enamel prisms (the rest of the work in making these into separate structures, always following from a mechanical disruption of the tissue structure[6]) relates entirely to the excentric secretory activity of the ameloblasts that exude the matrix proteins and simultaneously allow for mineralization with ~10,000 hydroxyapatite crystals per cell domain within this scaffold. The incredibly high mineral density of enamel leads to its post-mortem survival over all other body tissues, assuming that the local environment is not acidic.

### Imaging Cutting Interactions

Having put modern operative dentistry firmly into its pre-historical "background," it would be useful to look at some of the work that has attempted to image the cutting of these dental hard tissues. There are thousands of papers that have examined the after-effects of preparing hard tissues, whether by hand or by rotary instruments, chemical "conditioning" or, more recently, lasers. However, there have been few attempts to record the effects of cutting interactions with tooth tissue as it occurs.

#### *Imaging Slow Speed Cutting Interactions*

The cutting of any material will depend on a suitably hard instrument with a "sharp" edge applied to the substrate at the correct angle, having sufficient force to cause removal of the material. Imaging this sort of cut-

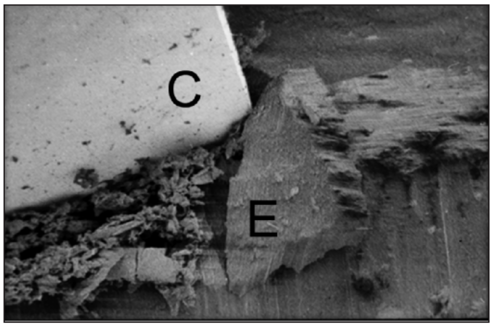


Figure 3. *Still image from a video enamel cutting taken within a SEM. The enamel (E) is crushed by a tungsten carbide chisel (C). SEM Fieldwidth 250 μm.*

ting can be undertaken using many types of microscope, including dissecting ones onward, but the best resolution for surface detail will be achieved using the scanning electron microscope (SEM).

The first, and probably only useful SEM recordings of cutting interactions was made by the last author, with a Cambridge Instruments "Stereoscan 1" at the University College London between 1967 and 1985. Using this instrument, the electron-optical column was isolated from the sample chamber so that the two spaces could be pumped separately. Normally, these had to have the correct vacuum, but this early SEM could be operated by disconnecting one vacuum sensor system so that the lower chamber had an "out-gassing" sample: for example, this became the first Environmental SEM (ESEM). All of this was undertaken at a low 2-3kV accelerating voltage, using electron beam deflection to give two viewpoints for TV rate depth perception using anaglyph stereo.[7] When cutting the dental tissues, an instrument was held at a fixed focal position in the SEM beam and the tooth sample was presented to the cutting edge. The net effect was to produce video footage that looked as if the "camera" was panning along the cutting interface as the experiment progressed. The main difficulty with this research material arose from the challenge of presenting the video footage to audiences at the time. As a consequence, this path-finding work has seldom been seen in the public domain. Figure 3 is a still image taken from a video showing the effect of tungsten carbide chisels on enamel, while Figure 4 shows the effect of an ultra-sharp diamond knife on an intact enamel tooth surface.[8]

Subsequent to this work, the mechanisms for cutting enamel have been attributed to fracture along various lines of weakness in its structure, with some degree of plastic deformation below the blade edge.[8-9] However, the use of SEM for studying cavity margins precluded the direct observation of any remaining subsurface cracking that may have occurred.

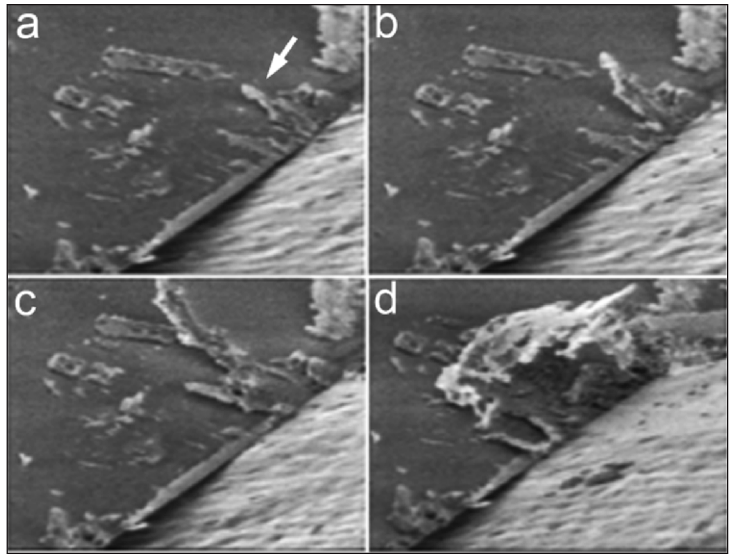


Figure 4. *A sequential series of images from a video showing a diamond knife cutting intact surface enamel in the SEM. The Tomes process pits are visible on the surface of the unworn tooth (bottom right). A slice of enamel prisms, cut at 90° to their long axis, slide along the blade edge (panel a, arrow), gradually pealing off as a layer (panel d). SEM Fieldwidth 100 μm.*

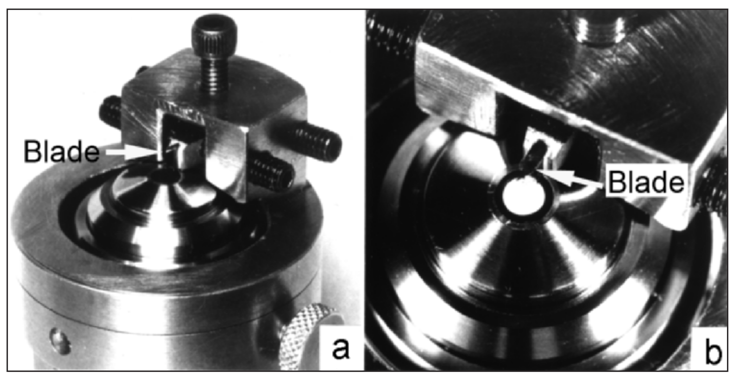


Figure 5. *Fixture for confocal reflection imaging of cutting with a diamond blade. The blade (arrow) was held at the focal point of the immersion objective and the enamel sample was driven onto the blade using a micro-positioning device.*

In a similar manner, the first author developed a technique for imaging the effect of a diamond blade on enamel using video-rate reflected light-confocal microscopy to image the enamel prism structure below the sample surface as it was being cut.[10] Confocal microscopy is an ideal method for examining the subsurface features of dental hard tissues at resolutions between those of conventional optical and electron microscopy.[11] In these experiments, as for the SEM imaging, the blade was held at the focal point of the immersion objective, and the enamel sample was driven onto the blade using a micro-positioning device (Figure 5). The anisotropic nature of enamel became

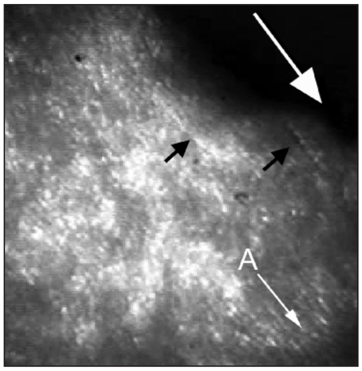


Figure 6. *Reflection confocal microscopy image of a diamond knife cutting along a line parallel to the enamel prism axis (A). Cutting shows relatively simple fracture patterns (black arrows) along prism boundaries. TSM x 20/0.80 NA oil Fieldwidth 400 µm.*

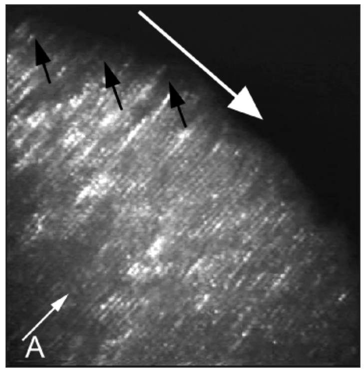


Figure 7. *Identical setup to Figure 6 except that the cutting axis is perpendicular to the prism axis (A). Cutting leads to multiple crushing and collapse features as prisms shear and fragment, leaving a rough surface (black arrows). TSM x 20/0.80 NA oil Fieldwidth 400 µm.*

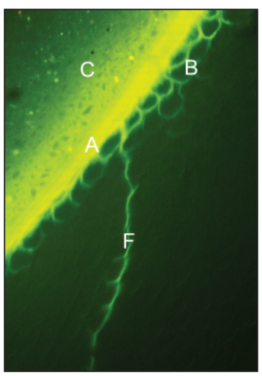


Figure 8. *Laser confocal fluorescence image of a Lucifer Yellow labeled dental adhesive resin layer (A), penetrating enamel prism boundaries (B) and exploiting an enamel fracture (F). The overlying bonded composite (C) shows mixing from the fluorescent labeled air-inhibited component of the adhesive. Shrinkage of the composite restoration could lead to fracture of the enamel prisms due to their relative weakness in their long axis. Yokogawa CSU10 x 60/1.40 NA oil. 488 nm illumination 510 nm bandpass filter. Fieldwidth 150 µm.*

immediately apparent, with different prism axes presented to this ultimately sharp instrument. When cutting along the prism axis, enamel broke relatively easily, but cutting across prisms produced a crushing/crumbling failure of the structure (Figures 6 and 7). These two axes are equivalent to using a chisel along the vertical walls and cervical margin of a proximal cavity.[8] Trimming the cervical margin with a chisel seldom produces a microscopically smooth surface. In all cases, subsurface cracks were apparent, driven below the cut surface. With the occurrence of such cracks, there would be an increased risk of leakage and gap formation at the tooth/adhesive restoration interface during dynamic loading or following shrinkage of a restorative material. As can be seen from the above experiments, in many parts of a cavity, the enamel prisms are parallel with the cavity surface and potentially defective in their cohesion with the body of the tooth structure.

The gold standard for bonding resin composites is the acid-etch technique, as first described by Buonocore.[1] However, potential pitfalls arise, because of the difficulty in achieving resin infiltration to the depth of the etch penetration.[12] A further confounding effect arises, because of the relative strengths and weaknesses in enamel structure.[13] Enamel prisms are very strong in their long axis, mainly attributable to the predominant axial orientation of the extremely long hydroxyapatite crystals; however, they are relatively flexible when subjected to side loading and stresses. A cavity margin showing subsurface cracking may be subject to imperfect resin infiltration and subsequent failure due to shrinkage of the conventional composite materials. Figure 8 shows a fluorescent labeled adhesive penetrating into very superficially etched enamel. The presence of a crack below the surface would easily lead to cohesive failure of the enamel. The clinical manifestation of this effect is seen as a white line around a margin, due to light reflecting from the fractured interface. This usually becomes apparent upon polishing the restoration and may subsequently lead to staining.

The previous lack of appropriate instrumentation is probably responsible for the remarkable dearth of studies of bur/tooth interactions, which have recorded microscopical changes at the interface as they occurred.[14-15]

*Imaging High Speed Rotary Cutting Interactions*

Video rate confocal microscopy has been used to study the high-speed cutting interactions (up to 300,000 rpm) between dental burs and tooth substance below the surface of the specimen. A stage was designed and built that allowed the end of a dental bur to be observed as it cut into the tooth substance[16-18] (Figure 9). This has been developed to also allow for simultaneous recording of

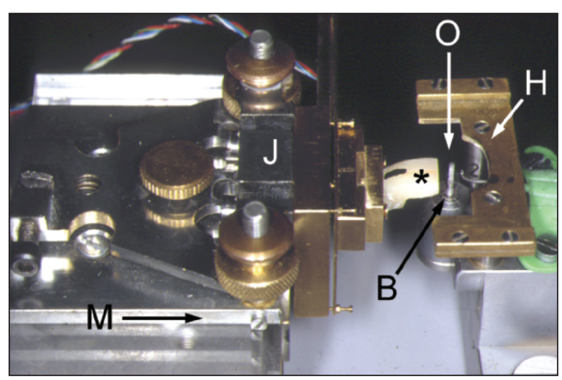


Figure 9. *A custom-built stage for microscopically imaging the cutting of enamel by a turbine driven dental bur (B). A tooth (*) is secured on a tripod jig (J), allowing the upper surface of the enamel specimen to be precisely levelled perpendicular to the optical imaging axis (O). A DC micromotor-driven ball race carriage (M) drives the tooth onto the bur – imaged through a protective cover glass in a holder (H) with coolant water below and an oil or water immersion objective lens above the glass window.*

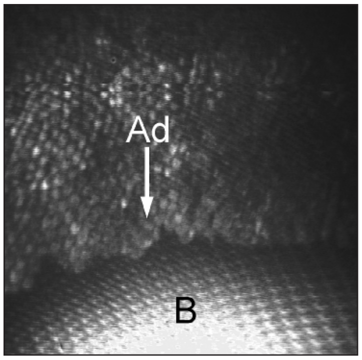


Figure 10. *Image from a realtime cutting movie using the setup in Figure 9. The fast clockwise rotating tungsten carbide bur (B) appears as an interference pattern because of the TSM scanning disc. Enamel prisms (E) show cutting with their long axis parallel to the bur. The tooth sample advances (Ad) onto the bur. TSM x 20/0.80 NA oil Fieldwidth 400 μm.*

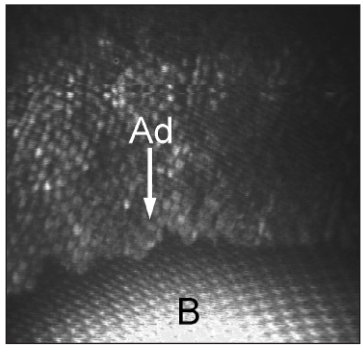


Figure 11. *Higher magnification image of the advancing front/exit of enamel cut with a diamond bur (B). Cleavages of 2-4 prisms depth are shown being plucked from the finish surface as the bur rotates cutting clockwise and the specimen advances (Ad). TSM x 50/1.00 NA Water Fieldwidth 180 μm.*

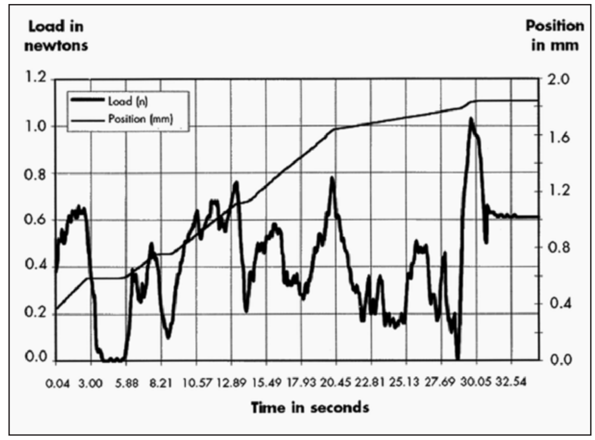


Figure 12. *Graph showing the faltering progression of a tungsten carbide fissure bur cutting (thin line) at a high advance rate (5 mm/minute) versus load (bold line). The air turbine is overloaded. The load is fluctuating widely and the progression is erratic in order that the cutting could continue. Courtesy of the* British Dental Journal.

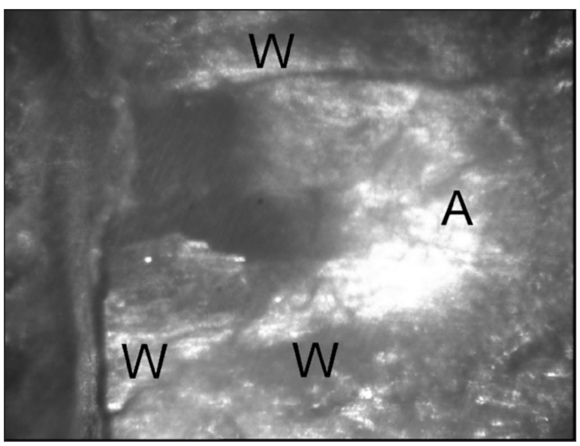


Figure 13. *Still image from a video sequence of enamel ablated by Er:YAG laser at 350 mJ, recorded at 60 frames per second (twice video rate). The enamel shows severe cracking both at the advancing front of the cavity (A) and parallel to the cavity wall (W). TSM x 24/0.60 NA Glycerin Fieldwidth 400 μm.*

the applied load with the position of the bur within the tooth. The risk of damaging the front lens of an objective was reduced by holding the rotating bur in a fixed position under the microscope objective lens, while the sample was advanced onto the bur; the observer interpreting the image as if the bur was being moved into the tooth, as would be expected in a normal situation.

This apparatus has allowed studies to compare the cutting interactions of diamond versus tungsten carbide (TC) burs,[16,18] showing that both types of bur lead to subsurface cracking, as also noted by Xu and others.[13] The mechanisms by which dental burs cut enamel are apparently independent of enamel prism orientation; this factor only affects the direction of crack propagation and the roughness of the margins where the enamel is unsupported. The actual mechanisms of cutting differ, however, in that diamond burs cause groups of enamel prisms to be plucked out from the cavity wall in direct relation to the grit size of the bur; whereas, TC burs have a steadier removal pattern that may progress as a series of ripples through the interface (Figures 10 and 11). These ripples become waves and are far more apparent when the handpiece is less powerful and the bur is partly stalling: this would relate to vibration perceived by both the patient and the operator[18] (Figure 12). The excentric concentricity of the bur will also have a profound effect on the damage produced by cutting and, again, this has been imaged, along with a chip analysis of the debris produced.[17] The use of cheap burs, which are less than concentric, could cause serious enamel cracking, patient discomfort, shortening of bearing life in the handpiece and even fracture of the bur.

*Imaging Laser Cutting Methods*

More recently, video-rate confocal microscopy has been employed for pilot studies to examine the effects of lasers, such as Erbium YAG, on tooth tissue. This is technically somewhat difficult, as there is a significant risk of damage to the end lens of the microscope objective using such cutting techniques. Current configurations of the microscope have used *in vivo* long focal range objectives[19] in order to separate the cutting laser beam from the lens system of the microscope. These lenses have a working range of up to 8 mm and have internally focusable elements to select the plain of tissue on which to focus.[20-21] The laser pulses can be seen ablating the tooth tissue, and images also show debris fields along the cutting path. Severe cracking of enam-

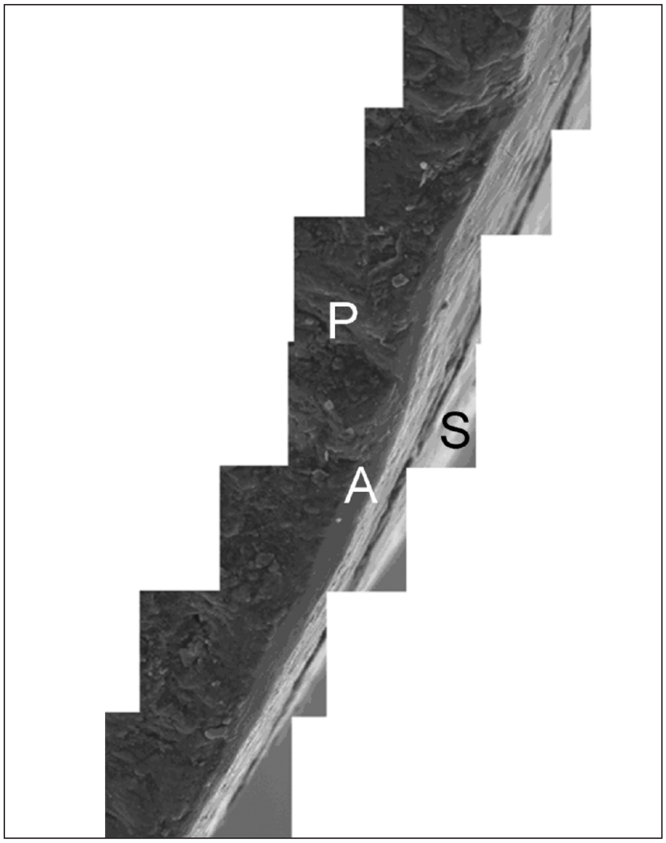


Figure 14. *Composite SEM image of adult enamel, perpendicular to the surface (S)–showing prismatic enamel (P) failing to reach the surface, instead being replaced by an aprismatic (A) surface layer. SEM x 3000. Fieldwidth of each component image: 80 µm.*

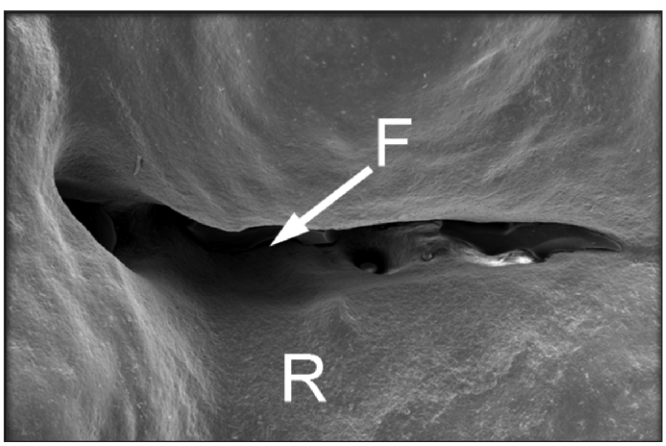


Figure 16. *SEM image of a bioglass air-abraded fissure showing the cleaned fissure (F) with minimal opening of the fissure but surface roughening (R) – leaving a finish ideal for bonding with adhesive resins. SEM x 25 Fieldwidth 5 mm.*

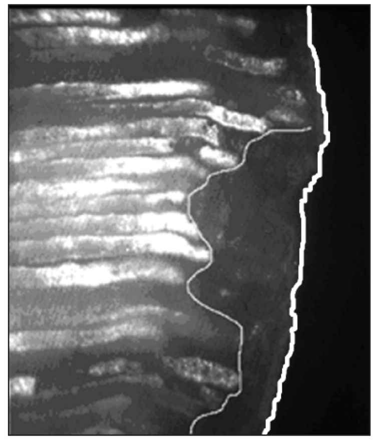

Figure 15. *Deciduous tooth demonstrating prism-free enamel between the prismatic enamel (thin white line) and the tooth surface (thick white line). TSM x 100/1.40 NA Oil Fieldwidth 85 µm.*

el at the advancing front of the cavity and in areas parallel to the cavity wall were visible following Er YAG ablation (Figure 13). Recording rates are currently up to 60 frames per second (twice the video rate), but there is clearly a need for increased speed of imaging and recording—a feature that is becoming more available with better camera sensitivity and ever increasing computing power.

### Less Traumatic Cavity Preparation Techniques: Air Abrasion

Air-abrasion is a technique that was "rediscovered" in the 1990s and has a number of useful attributes for modern, minimally-invasive dental techniques. Air-abrasion offers multiple benefits for cutting vulnerable materials with minimal temperature changes (+/-2°C) or vibration, thus minimizing the risk of cracking.[22-23] SEM studies reveal a typically roughened, pitted finished surface, devoid of classical substrate features, such as enamel prisms and dentin tubules.[24-25] Unlike rotary cutting instruments, the principle action of air-abrasion has been demonstrated as end-cutting.[26-27] It is generally considered that hard particles will remove hard tissue, while soft particles will, respectively, remove soft tissue. Therefore, interest is recurring, using the principles of air-abrasion as a selective cutting technique, in targeting only softened diseased tissues.[24,28-29]

Air-abrasion is a pseudo-mechanical, non-rotary method of cutting dental hard tissues utilizing the transfer of kinetic energy from a stream of desiccated abrasive particles bombarding the tooth surface at high velocity. The conventional abrasive employed for cutting tooth structure is aluminum oxide ($Al_2O_3$: $\alpha$-alumina), with an average particle size of 27.5 mm and a hardness of 9 on the Mohs' scale. The exit pressure employed commonly ranges between 200-830 pascals (Pa), and this can impart a particle velocity in excess of 300 meters per second, depending on the diameter of the nozzle tip. The alumina escapes from the nozzle tip in a cone-shaped stream, the walls of which diverge from its long axis at an angle of approximately 3.5°. The dimensions of the cutting cone increase in proportion to the distance between the nozzle tip and the tooth surface due to the increase in particle scatter. However, the abrasion provided by the peripheral portion of the stream is less efficient, due to the lower velocity and concentration of the alumina particles.

Air-abrasion units can be used to readily cut dental hard tissues, and this can present control problems, as there is a lack of tactile feedback. Couple this with the

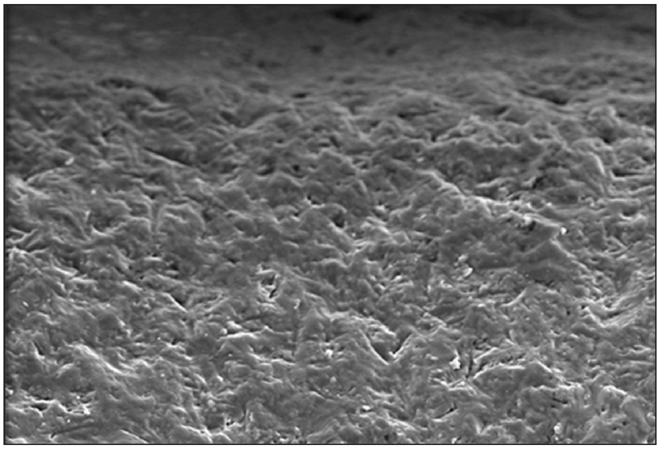

Figure 17. *High magnification image from the region (R) of Figure 16 showing a pitted, roughened enamel surface–ideal for bonding but by careful matching of the abrasive powder hardness to that of weakened carious enamel, there is limited removal of hard, healthy enamel. SEM x 300 Fieldwidth 290 µm.*

fact that commercially-used $\alpha$-alumina particles are inefficient removers of soft carious tissue, and one could easily enlarge a cavity in healthy tissue when it is clinically unnecessary. While current systems have full US FDA approval for the clinical use of 27.5 mm (or larger) alumina particles, there is a need for powders that are inherently safe, biocompatible and have "intelligent" cutting characteristics, in other words, powders that only remove diseased tissue.

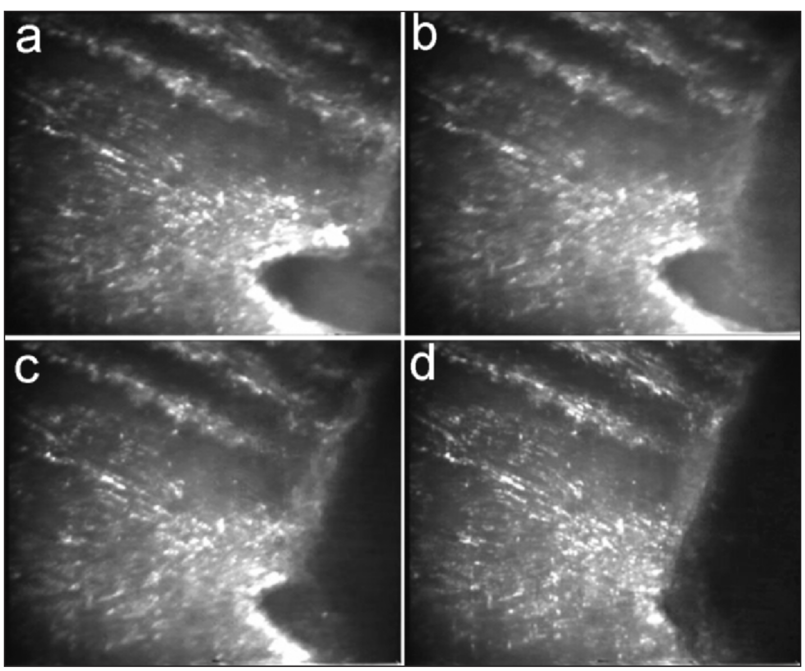


Figure 18. *Panel of four images showing the advancing front of a water-shrouded alumina air-abrasion cutting a longitudinally sectioned enamel fissure. The base of the enamel fissure is obliterated as the cutting proceeds. TSM x 24/0.60 NA Glycerin Fieldwidth 500 µm.*

**Management of Occlusal Caries**

The concept of minimal cavity preparation, which encourages the conservation of healthy enamel and dentin, has been dependent on the introduction, development and ready availability of adhesive restorative materials. The use of fissure sealants and preventive resin restorations is widespread, but anatomical features of the enamel fissure may conspire to reduce the effectiveness of the conditioning acids.[30] One feature that will reduce etching effectiveness is prism-free enamel, which may form in the outer layers (<100 mm thick) of enamel, reflecting lack of a Tomes' process at the secretory end of ameloblasts. Such prism-free enamel is especially prevalent in deciduous teeth and in the entrance to fissures (Figures 14 and 15). This has prompted a re-examination of the air-abrasion technique (and other techniques) as a suitable method for preparing the cavity and conditioning its surfaces. However, it is important to realize that this technique has limitations.

"Airpolishing" is an alternative type of air-abrasion and has some utility in occlusal caries diagnosis. In this technique, wet sodium bicarbonate powder is used instead of dry alumina. Baking soda is dissolved in water and easily removed. Airpolishing removes plaque and surface stains very effectively and is an excellent method for cleaning stained fissures, but it will not damage intact enamel surfaces.[29] The tooth can then be dried and the extent of any opacity in the decayed enamel due to caries can be readily assessed.

**Investigating or Abusing Occlusal Pits and Fissures?**

There are advocates for the use of air-abrasion in the detection and diagnosis of incipient pit and fissure lesions.[31] By directing a stream of abrasive particles into the bottom of pits and grooves on occlusal surfaces, the narrow width of the particle stream will cause negligible widening of the fissure walls. However, there is a growing body of opinion that disagrees with the decision to explore and restore teeth with minimal staining to which the explorer does not stick and is unable to penetrate. This is because one of the characteristic features of the alumina air-abrasion technique is that it cuts harder tissue more efficiently than soft tissue. While this statement is true for dentin and demineralized enamel is removed at a higher rate than sound enamel, sound enamel is still efficiently cut in a non-discriminatory manner, creating the potential to prepare a cavity where one did not originally exist. This distinctive feature makes statements that have promoted the use of air-abrasion on the basis that it "removes only decayed areas" and "allows permanent seal of

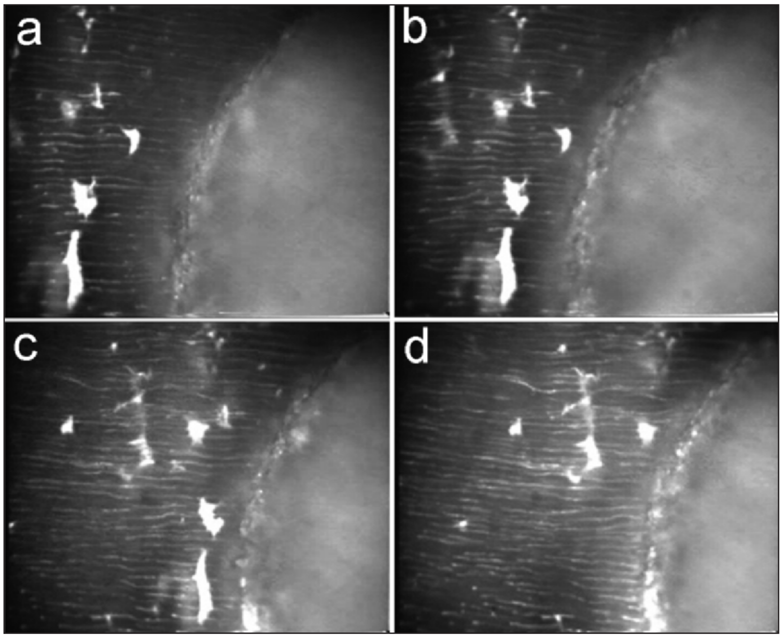


Figure 19. *Same sample as Figure 18, where the cutting process has now advanced into superficial dentin. Incompletely mineralized calcospheritic dentin is visible among the dentin tubules. The sample has been advanced from the left towards the cutting stream (S) on the right. TSM x 24/0.60 NA Glycerin Fieldwidth 500 µm.*

the less susceptible areas" unreliable.[32-33] Indeed, there is now some evidence to show that specific abrasive particles are required in order for air-abrasion to be effective in the more selective removal of softer carious tissue.[28]

**Application of Bioglass Air-abrasion to Fissure Investigation/Treatment**

Air-abrasion has generally utilized cutting with hard alumina particles or air-polishing with sodium bicarbonate. Other bioactive materials, such as Bioglass, could have profound effects on dental hard tissues if impacted into the tooth surface. These materials are well recognized for their bone-inductive properties,[34] are licensed for clinical use and have been demonstrated by toxicology studies to cause minimal pulmonary tissue reactions with breakdown and the safe excretion of inhaled glass components.[35] There is evidence that particles of Bioglass can interact with dentin: either tubular fluids or saliva, through the formation of a hydroxy carbonate apatite layer, which may provide an effective interactive seal. These novel ceramic materials can be manufactured by either a melt or sol-gel process[36] and can be modified by a number of intra- and post-production stages to increase or decrease their hardness. Therefore, this could allow for the tailoring of their properties for cutting hard substrates, such as enamel and exposed sound dentin, or soft substrates, such as carious dentin.

Initial laboratory studies investigating the potential selectivity of Bioglass air-abrasion for incipient enamel fissure caries have showed promising results. Scanning electron microscopic investigation of carious occlusal fissures prior to and after air-abrasion with Bioglass powder indicates a significant preferential removal of the damaged, demineralized enamel prisms, while leaving intact enamel margins (Figures 16 and 17). Thus, this powder, when used in an air abrasive device, has the clinical ability to discriminate incipient lesions from sound enamel, treating them selectively, and more importantly, minimally. This material now has FDA approval for use, and early stage clinical trials are underway.

*Imaging Air Abrasion Cutting Interactions*

The use of optical microscopes for imaging a cutting process that produces large volumes of dust does not, at first glance, appear to be a winning combination. However, devices have been made that allow for the observation of air abrasion as it is cutting into enamel and dentin, using confocal microscopy.[37] The sample is held in a static relationship to the air abrasion nozzle and the cavity is imaged as it is cut.

The design comprised a rigid dust containment chamber, whose internal pressure was maintained below atmosphere, despite air abrasion inflow pressures of up to 670 Pa. The vacuum within the chamber (generated by a commercial industrial vacuum cleaner) eliminated abrasive escape from instrument access portals.

The basic chamber comprised a simple rigid acrylic box: 20 x 35 x 5 cm, with two close fitting lids. The glass microscope slide, to which the specimens were stuck, using the thinnest possible film of low viscosity clear cyanoacrylate adhesive, was clamped in place between the inner and outer lids. Centrally cut access windows allowed for specimen imaging and alignment of the air abrader nozzle to the specimen.[37]

Thus, the design allowed for the viewing of serial specimens through a glass window, and the flexible handpiece seal (dental rubber dam) allowed for re-alignment and several cutting attempts into each specimen. Flat polishing the air abrader head allowed the 450 µm bore nozzle orifice to come within 500 µm of the glass base plate, maximizing the depth of focus into the cut substrate.

To allow for real time direct reflection imaging of the cutting interactions, a Tandem Scanning confocal Microscope–TSM (Noran, Madison, WI, USA) was employed with 100W mercury arc illumination. This instrument had previously been modified for horizontal *in vivo* imaging.[18] The use of internally-focusable long working distance objective lenses of the "Hill" type: 16x/0.45 NA; 8 mm working distance and 24x/0.6 NA;

1.4 mm working distance[15] allowed imaging through the glass slide into the tooth structure. The images were captured with low light level CCD cameras and recorded digitally.

Specimen imaging through the microscope slide and clear cyanoacrylate adhesive was therefore straightforward. The specimens were hand-polished to a P1200 grit surface finish prior to mounting, as trials had shown superior imaging of the internal structure in teeth when using this method. As had been found in earlier work, transparent adhesive systems do not adversely affect confocal imaging and may possibly assist within the depths of specimens.[38]

Imaging with this configuration has allowed observation of the "nibbling" type of tissue removal apparent with air-abrasive particles. Subsurface cracking is visibly reduced compared to that found with rotary and laser-based cutting methodologies. It has also been possible to record air-abrasive cutting interaction when the particle stream is shrouded by water spray. This technique uses a concentric nozzle arrangement, with water acting as a curtain to restrain powder scatter—a serious challenge with conventional air abrasive techniques. The water spray can either be delivered under pressure, or it can be alternatively drawn through a small side port in a disposable concentric plastic nozzle by using the Venturi effect derived from the powder-air stream.[39] Imaging this variation on the air abrasive cutting technique has shown that there is a fall-off in cutting efficiency beyond a certain distance from the cutting nozzle, as mixing the water and powder creates a low energy slurry. Prior to this point, efficiency is not impaired and, indeed, cutting rates are improved. This may be due to the agglomeration of particles leading to the removal of tissue in larger blocks than would be expected from the size of the individual particles (Figures 18 and 19).

## CONCLUSIONS

This review of cutting procedures for dental hard tissues has shown that, while there are plenty of papers that have examined the effect of different cutting procedures on dental hard tissues, very few have actually examined the mechanisms at work as they occur. The ability to undertake cutting as it occurs by using video-rate confocal microscopy has shown how the structure of enamel (in particular) influences the way in which a cutting instrument works. The cutting of dentin is clearly more straightforward, as it is so much softer and isotropic in its physical characteristics. The volume of literature that reports on adhesive interactions with dental hard tissues is truly immense, but seldom is the variability of the enamel structure accounted for in this work. Future studies should take such anatomical variations into account. Equally, the need for preparation methods that do not endanger or seriously abuse the dental substrate remains a challenge for operative dentistry in the 21st century.

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