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Review

Cite this article: Atmeh AR, Watson TF. 2016 Root dentine and endodontic instrumentation: cutting edge microscopic imaging. *Interface Focus* **6**: 20150113.
http://dx.doi.org/10.1098/rsfs.2015.0113

One contribution of 14 to a theme issue 'Cutting science in biology and engineering'.

Subject Areas:
bioengineering

Keywords:
endodontics, root canal treatment, rotary files, real-time confocal imaging, dentine cutting, cleaning and shaping

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Root dentine and endodontic instrumentation: cutting edge microscopic imaging

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Cutting of the dental hard tissues is an integral part of restorative dentistry. Cutting of the root dentine is also needed in preparation prior to endodontic treatment, with significant commercial investment for the development of flexible cutting instruments based around nickel titanium (NiTi) alloys. This paper describes the evolution of endodontic cutting instruments, both in materials used, e.g. the transition from stainless steel to NiTi, and the design of the actual instruments themselves and their method of activation—by hand or motor driven. We have been examining tooth-cutting interactions microscopically for over 25 years using a variety of microscopic techniques; in particular, video-rate confocal microscopy. This has given a unique insight into how many of the procedures that we take for granted are achieved in clinical practice, by showing microscopic video images of the cutting as it occurs within the tooth. This technology has now been extended to allow imaging of the endodontic instrument and the root canal wall for the first time. We are able to image dentine distortion and crack propagation during endodontic filing of the root canal space. We are also able to visualize the often claimed, but seldom seen action of contemporary endodontic instruments.

1. Introduction

Endodontics is the dental specialty concerned with the prevention and treatment of pulpal and peri-radicular diseases [1]. These diseases affect, respectively, the tissues encapsulated within the hard dental tissues as well as those surrounding the roots; the periodontal ligament and alveolar bone [2]. In order to maintain a functional tooth, root canal treatment is the most commonly performed procedure. It involves a sequence of steps that require accessing the encapsulated pupal tissues, then preparing and disinfecting the accessed space and canals. It eventually aims to create a sterile space that retains a sealing/filling material to prevent further infection or reinfection [3].

Over the years, a wide range of root canal preparation approaches have been suggested and used, ranging from instrumentation-free approaches to heavy instrumentation [4] following an access having been cut though the crown of the tooth. These approaches have variously combined mechanical preparation of the canals and chemical treatment with disinfectants and medicaments, and are therefore described as chemo-mechanical preparation techniques [3]. Despite many improvements and developments, the optimal objective of obtaining a bacteria-free root canal space has proved to be difficult to achieve, if not almost impossible [5–7]. One major factor is the anatomical complexity of the root canal system. The root canal system is comprised of single main canals centred within each root, which vary in diameter, curvature and degree of lateral branching [8,9]. This complex structure causes unpredictable access for stiff instruments and chemical disinfectants to all the anatomical features. This is further complicated by the lack of optimal root filling materials which can compensate for suboptimal preparation by sealing tightly the prepared root canal space to prevent fluid permeation [10].

In this review, we shed light on the process of dentine cutting during endodontic treatment, and the different mechanical techniques used in this context. It presents preliminary studies that may offer a better understanding of the interaction between endodontic cutting instruments and dentine, through employing high-resolution microscopic imaging in real time.

2. The workpiece: root dentine structure

A tooth consists of the outer enamel covering, which is supported by the dentine core, this making up the greatest proportion of the tooth [11]. The major structural unit of dentine is the dentine tubule, running from the enamel–dentine junction (EDJ) to the pulp. This 1–2 μm diameter tubule conveys pulpal fluid from the pulp to the enamel, so maintaining the hydration of the tooth, and other physiological mechanisms such as the transmission of sensitivity. Dentine is a hydrated material either by the inherent outward flow of pulpal fluid or via permeability from the root surface in a tooth that has had the pulp space obturated. Tubule density at the EDJ is 19 000 mm^2 and increases towards the pulp to 45 000 mm^2. The diameter of the tubule also increases from 0.8 μm at the EDJ to 2.5 μm at the pulp. As a consequence, there is much more inter-tubular dentine in the outer dentine than near the pulp. In the outer two-thirds of the dentine, a thin coating of highly mineralized peritubular (or intra-tubular) dentine surrounds the tubule itself. The bulk of the dentine consists of a matrix of type 1 collagen embedded in hydroxyapatite crystals, so forming the inter-tubular dentine. Hyper-mineralization of dentine will occur as a defence reaction to caries and tooth wear in the crown of the tooth. This reduces permeability and confers a protective function, preventing noxious substances entering the pulp. In the root of the tooth the peritubular dentine becomes particularly noticeable and thicker with age, so making the tooth root more mineralized, and also more brittle. Dentine is neither strong nor weak in any particular direction: it is resilient, hence as ivory, the material can be beautifully carved [12].

3. The cutting tools: endodontic instruments

The rationale for root canal treatment is a combination of biological and mechanical preparation of the root canal system [3]. The biological aspect is achieved through eradicating the pulpal tissues and bacterial products, while the mechanical aspect is mainly concerned with the shaping of canals into a more uniform and conically tapered space [13]. This space is prepared to contain the root filling material and allow more of the antimicrobial irrigating agents to flow deep into the canals.

Since the earliest documented endodontic instruments, which refer back to the nineteenth century [14], the basic concept of canal preparation has remained the same. A sequence of narrow and tapered metal 'broaches' with cutting edges on the sides act on rotation (reaming motion) or in an in-and-out (filing) motion inside the canals. These manually- or motor-operated metal cutting instruments, which are called endodontic files, have been produced with a wide variation of designs, materials and cutting properties [4].

3.1. Endodontic instrument materials

Until recently, stainless steel, a stiff alloy, was the most commonly used material for the manufacturing of endodontic files. The physical properties of the machined endodontic files, however, vary depending on the alloy composition, size (diameter) and geometry of the file [15]. The elastic modulus for stainless steel files is around 340 $\pm$ 30 GPa, and their hardness is around 6.5 $\pm$ 0.5 GPa [16].

In terms of the requirement for dentine cutting, which has a hardness of around 0.5 GPa [17], the use of stainless steel that has much higher hardness is in excess of what is actually needed. When it comes to elasticity, stainless steel files are also much too stiff to follow complex root canal architecture. With high elastic modulus, the rigidity increases rapidly as files get larger with unwanted overcutting of dentine [18] that can cause more aberrant preparations and unfavourable instrumentation outcomes [19,20]. This problem is significant when instrumenting curved roots with large and stiff files, where more forces are conducted laterally while the file is tending to restore its original shape so causing excessive dentine cutting at the outer curvature of the root [21].

In the last two decades, stainless steel has been gradually substituted by a more elastic alloy, nickel titanium (NiTi). William Buehler and Frederick Wang developed NiTi, or nitinol, in 1959. It is a superelastic alloy that is composed of an equal atomic ratio of nickel and titanium [22]. NiTi was first used in dentistry in 1971 as orthodontic arch wires for the alignment of teeth [23]. In 1988, the first NiTi file was produced as a hand file [24], but because of its superior flexibility, NiTi files have also been widely developed as motor-driven instruments, whereas stainless steel instruments would fatigue and fracture if continuously mechanically rotated in a curved root canal.

The mechanical properties of NiTi depend on its crystallographic arrangement, which can exist in two forms depending on the temperature and stress. At higher temperatures, NiTi exists in an austenitic phase, where the atoms are arranged in a body-centred cubic lattice [22]. When stress is applied or temperature is reduced below a certain range—described as the transformation temperature—the atoms tend to rearrange their distribution into a more elastic form called the martensitic phase. This transformation is what gives the NiTi its superelasticity. With an elastic modulus of 120 GPa, austenitic NiTi is much more flexible than stainless steel and under stress it can transform into the more flexible martensitic phase, with an 80 GPa elastic modulus [22].

3.2. Manufacturing and design

Developments in endodontic instrumentation have been driven by the need for improved canal preparation techniques in order to minimize unwanted dentine cutting that can affect the treatment outcome [25]. Therefore, NiTi alloy has become the preferred manufacturing alloy with its superelastic properties and lower hardness of around 3.17 $\pm$ 0.2 GPa [16]. This has allowed better negotiation of curved canals and complex anatomies [26], and minimized transferring the applied stresses laterally into the dentine [19]. Developments have also included other aspects such as the design and manufacturing procedures.

Endodontic files are manufactured using two main processes, either through machine grinding of tapered metal wires, or by a combination of grinding and twisting [27]. Stainless steel files are usually manufactured using both techniques; however, for NiTi twisting was obviously not initially applicable because of the superelasticiy of this material. However,

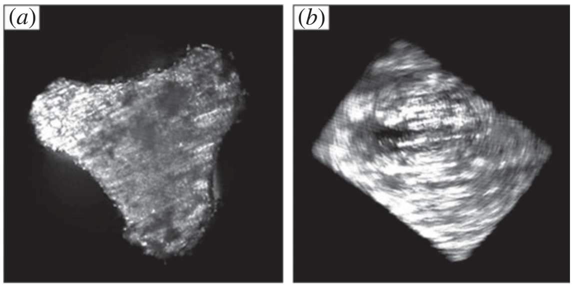

Figure 1. Still images of horizontally sectioned NiTi files demonstrating the cutting features of two different types of NiTi files. (*a*) A triangular cross-section design with three cutting edges separated by flutes to allow chip clearance (ProTaper® Universal—Dentsply International). (*b*) A rectangular design allows two edges to be cutting at once while the file rotates eccentrically (ProTaper.Next®—Dentsply International).

twisted NiTi files have been produced after developing a special thermal treatment of the alloy [28]. Other advancements in the manufacturing of NiTi files involved thermomechanical processing which allowed the use of these files in the martensitic phase providing a new generation of files with improved properties [29].

The cutting features of endodontic instruments can be more easily visualized by examining transversely cut sections of these files (figure 1). These section images will vary depending on the level of sectioning. The outer diameter of endodontic files increases gradually over their length from the tip to the shank. The amount of this change—described as taper—is represented by a percentage that indicates the amount of change in the diameter (in hundredths of a millimetre) for every millimetre away from the tip. In certain designs, the taper can be variable rather than fixed. As the taper is correlated with the diameter, the file's rigidity can be highly affected by taper; the higher the taper the less flexible is the file. Therefore, some file designs increased the depth of the chip clearing flutes so reducing the bulk of metal in the central axis of the file to minimize the stiff metal effect on the file's flexibility.

The design of a file cross section can reflect its cutting properties and efficiency. Most of the stainless steel hand files have either triangular or square-shaped cross sections [27]. In these files, the cutting edges are perpendicular to the dentine surface, which is described as a passive cutting angle. The Hedström files, on the contrary, cut dentine aggressively with a linear filing or rasping motion due to their positive cutting angles with the dentine. In NiTi files, the design is much more variable: the angle of cutting edges or the 'rake angle' can be negative, or in a very few designs positive [30]. Other variables include the number of cutting edges, and the size of the flutes which are the spaces between the cutting edges that allow clearing of the debris during cutting (figure 1).

In addition to the shape of the cross section, NiTi files can also vary in the presence of additional features such as radial lands which are projections from the central axis of the file that are added to prevent screwing of the file into the root canal space while cutting [31]. The helical angle of the cutting edges is another feature, which can have a dissimilar pattern in some designs to again overcome a 'pulling-in' or 'screwing' effect [32]. The pitch is the distance between two adjacent cutting edges within which the pattern is not repeated, it represents the repetition of cutting edges within specific distance. The pitch size is correlated with the taper, helical angle and flute size, which therefore can be constant or variable.

3.3. Cutting processes with endodontic files

Whether in cross-sectional design, mode of action or materials, much research and development has been directed towards the cutting efficiency of these instruments. Different techniques have been used for the evaluation of cutting efficiency such as: weight loss measurements [33], scanning electron microscopy [34], and computer image analysis for before and after radiographs [35] and photographs [36]. These studies compared the differences in canal shape and volume before and after instrumentation. However, they did not examine the cutting mechanisms of these instruments, nor evaluated the interaction between cutting instruments and dentine. Indeed, there are very few studies that have directly examined the cutting interactions of endodontic instruments.

The cutting mechanics with hand-held stainless steel files may vary from those of motor-driven rotary NiTi files. The stainless steel hand files are rotated between the operator's fingers with a very low speed and variable forces, which are totally dependent on the clinician's dexterity. Looking at the cross section of these files the rake angle of the cutting edges can be neutral or positive, depending on which part of the spiral cutting edge is being examined. There are many different manufacturers of endodontic instruments named either by abbreviated expressions or eponymously. The so-called stainless steel 'K-files', for instance, have both triangular and square-shaped cross sections, while the eponymous, aggressively cutting 'Hedström' files, that cut with a rasping action, have usually a round cross section with a notch that gives a positive rake angle for these instruments: in side view they have a shape similar to a Christmas tree.

When a stainless steel K-file is used, the cutting motion can be performed with two modes of action. Either in a rotating motion (reaming), which allows the use of the angled cutting edges of the files in a horizontal action, or the file can be used in an in-and-out 'filing' motion, which uses the angled cutting edges in a vertical action. Cutting in these ways could be considered as a free diagonal, where the cutting edge is inclined at a certain angle [37].

During instrumentation with a positive rake angle file, cutting begins with the penetration of the cutting edges of the rotating file into the surface of the root dentine [38]. This will start an elasto-plastic deformation until the dentine's shear strength is exceeded by the force applied by the file and causes the separation of dentine chips running off the rake face [37]. With this cutting action, the surface infected dentine is removed to expose deeper layers that harbour bacteria so allow deeper permeation of the chemical disinfectants. Cutting is dramatically increased with the increase in the rake angle [39]. When preparing the root canal with a negative or neutral rake angle file, the cutting mechanism might be slightly different. As there is no engagement or penetration of dentine, rather it is described as a burnishing or scraping motion [39], which therefore requires more energy to cut dentine compared with instruments of positive rake angles [40].

Despite the development and variation in available endodontic cutting instruments, clinical studies have shown no statistically significant impact of the type of instrumentation used for mechanical preparation on the success or failure of the treatment [41–44]. However, these findings have been contrasted by microstructural analysis of prepared root dentine, which demonstrated microstructural effects of instrumentation that varied between the different types of files [45–47], and confirmed their impact on the mechanical properties of remaining radicular dentine [48]. These findings were also supported by micromechanical investigation of contact stress distribution on dentine [49]. This contrast between the findings of clinical and laboratory-based studies reflects the ambiguity in the correlation between the cutting properties of endodontic instruments and their clinical performance, which is potentiated by the lack of an appropriate investigative method.

It is difficult to determine how dentists choose what type of endodontic instrument to use, most choices perhaps being made on the basis of clinical simplicity, personal recommendation by experts in the field or even cost—where speed of application may be a major factor. If dentists were able to visualize the cutting mechanisms at work during endodontic procedures, then their choice of instrumentation could be more informed.

4. Imaging dental cutting

Stress–strain recordings during instrumentation of simulated canals [49–52] have been applied to evaluate the dynamic effect of endodontic instrumentation on dentine [53]. These studies may give a better understanding for the behaviour of instruments inside the canals, but they do not provide direct evaluation for the cutting process, something that cannot be achieved without real-time imaging. For this purpose, a novel microscopic live imaging technique has been developed and evaluated for the study of root canal shaping and dentine cutting.

There have been remarkably few studies that have imaged the interactions between dental cutting instruments and tooth tissue. This may be due, in part, to the difficulties attendant on imaging such small instruments at work; also taking into account that a dental turbine may be operating at cutting speeds of 200 000 r.p.m. with a bur typically less than 1 mm in diameter. We have published a number of papers illustrating the cutting interactions of dental burs with enamel using burs of variable geometry [54], both high and low torque hand pieces [55] and a slow speed diamond blade [56]. Previous work by Boyde [57] has shown the effects of cutting dental tissues using scanning electron microscopy evaluation. The unique aspect of our studies has been the application of video-rate reflection confocal microscopy for imaging the cutting interactions [58]. However, this technology has not been applied to the imaging of dentine while being cut.

The developed technique allows real-time imaging of the cutting process using a tandem scanning confocal microscope [59]. A special apparatus has been designed to fix a transversely sectioned root facing the objective lens while mounted inside a brass ring, held rigidly at the focal point of the long working distance lens being used. A gentle air stream may be used for chip clearance, or not—if the development of chips and debris is required. The file is introduced into the root canal space gradually with constant rate using a controlled stage to which the endodontic motor hand piece is attached in alignment with the root canal and the focal line of the imaging set-up, while the end view of the cutting process is observed. This set-up allows imaging of the root dentine inner surface in contact with the shaping endodontic files while recording the cutting process using a high speed camera (figure 2). Captured videos can be used to evaluate the cutting process in separate image frames and allow evaluation of the cutting process in the dentine. Using this set-up in the form of an open system will allow collecting the debris and produced chips that can be used for chip analysis [54,60], and wear particle analysis [61], as well as observing and studying microstructural changes such as crack formation and propagation (figure 3). The continuous clearance of debris, however, does not imitate the instrumentation in the closed system of root canals *in vivo*. Our cutting experiments are likely to produce

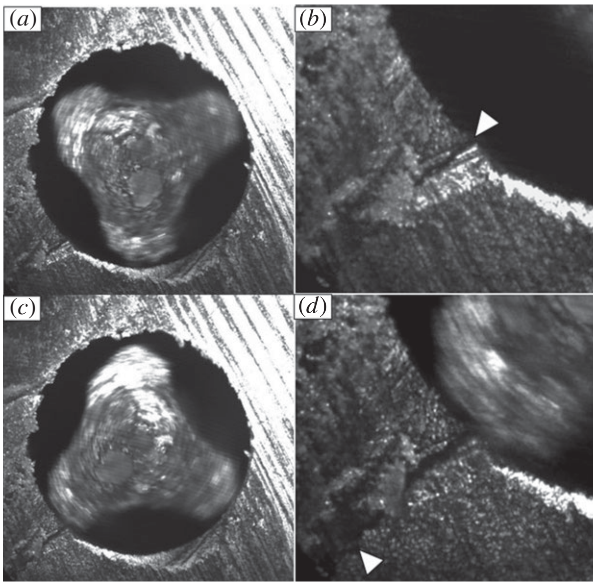

Figure 2. Viscoelastic behaviour of dentine during instrumentation: (*a*) a still image of a rotary NiTi endodontic file showing the cutting edges and flutes within the canal; however, not all the edges are actually cutting, only the upper right one is touching the dentine wall at that point. Width of field is 850 μm. (*b*) A higher magnification of the area in the lower left corner of (*a*) demonstrates the presence of initial crack at the canal wall (white arrow). (*c*) With further rotation of the file, two cutting edges are now touching the dentine (lower part of preparation), the lower left one has caused propagation of the crack laterally and compressed dentine which recovered its original shape because of its viscoelastic properties. (*d*) A higher magnification of the area in the lower left corner of (*c*) showing the widening in the crack (white arrow) as well as it propagating laterally when compared with (*b*).

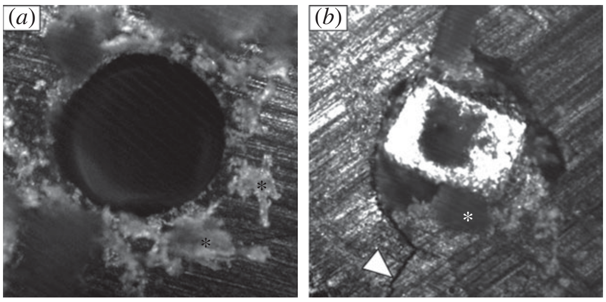

Figure 3. Chip and crack formation. (*a*) Sectioned root surface after endodontic instrumentation showing debris (chips) formed (black asterisks). Collecting and analysing these chips would provide valuable information to understand the interaction between the endodontic instruments and dentine. (*b*) An endodontic file at the beginning of the cutting process, showing massive amounts of debris clogging the space between the instrument and the dentine walls (white asterisk). Additionally, there is an established crack at the lower left corner (white arrow).

an optimized result, but it would not be unreasonable to suggest that the clinical situation would be even worse.

The significance of this imaging technique lies in its potential to provide better understanding of the nature of the interaction between the shaping instruments and dentine. This would provide the missing link in correlating the clinical performance of endodontic files with their impact on cut dentine. It also allows the observation of microscopic changes affecting the dentine, such as micro-crack formation and propagation.

5. Conclusion

In conclusion, studying the performance and cutting efficiency of the different types of endodontic files and instruments is essential in order to understand their impact on machined dentine. These instruments have undergone a continuous evolution, both in terms of cutting edge design and also in the materials used over the last 30 years, from hand instruments made of stainless steel to rotary powered NiTi files. With the current available evidence, there is an apparent gap between our understanding of the cutting technologies employed in endodontic treatment and the long-term clinical outcome, perhaps due to the lack of a dynamic evaluation of the cutting process. However, with the suggested real-time microscopic imaging, this discrepancy could be resolved, allowing a better understanding of the nature of the interaction between endodontic cutting instruments and dentine, leading to a proper evaluation of instrument design and manufacturing limitations.

Authors' contributions. A.A. participated in the design of the study and drafted the manuscript; T.W. participated in the design of the study and drafted the manuscript. Both authors gave final approval for publication.

Competing interests. We declare we have no competing interests.

Funding. We received no funding for this study.

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