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The role of mechanical instrumentation in the cleaning of root canals

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The cleaning and shaping of the root canal is a key procedure in root canal treatment. The aim of cleaning is the removal of tissue remnants and bacterial biofilms in order to allow close adaptation of the root filling to the canal walls. In simple straight canals with a round cross-section, this aim is easily attained by mechanical instrumentation and irrigation. The task of cleaning presents a greater challenge in oval canals, curved canals, and in canal systems that contain an isthmus. In areas that are inaccessible to mechanical instrumentation, the cleaning greatly depends on the action of sodium hypochlorite, which is used to dissolve and remove all of the remaining tissues and bacterial biofilms. Traditional irrigation with syringe and needle is often ineffective in cleaning such inaccessible areas. Newer irrigation methods allow for better cleaning by facilitating a more effective flow of irrigants; nevertheless, adequate, larger, mechanical preparations are required for the effective use of these methods. An alternative approach is to use a hollow file that adapts itself to the cross-section of the canal, without excessive enlargement of the canal, thus allowing mechanical scrubbing of the walls with a continuous flow of the irrigant through the file. All cleaning methods reach their limit in cases of long narrow isthmuses that are often inaccessible to mechanical instrumentation; adequate instrumentation is, however, a prerequisite for all cleaning methods.

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Introduction

If root canals could be thoroughly cleaned using irrigation alone and effectively obturated, there would be no need for mechanical instrumentation (1). However, with the currently available technologies, this is not yet clinically possible (2). Various forms of mechanical instrumentation have been used over the years for "cleaning and shaping" root canals. Mechanical instrumentation is often thought of as a means to facilitate root canal obturation by "shaping" the canal to accommodate certain types of master cones or certain types of pluggers. Nevertheless, it is recognized that cleaning and disinfecting of the apical part of the canal with irrigants such as sodium hypochlorite is ineffective unless the canal is instrumented to a given size (3–9).

Previously, extensive instrumentation was the hallmark of good endodontic treatment (3,6,10–12). Over the years, it became recognized that extensive removal of dentin tends to weaken the root and should be avoided (13–16). This realization led to a narrower ideal "look" of the root canal filling. The question about the appropriate amount of dentin to be removed for adequate cleaning is still debated (3–9,17). The adequate apical size and proper taper of the rotary instrument are still not settled (6,9,17,18). Recently, a new concept of mechanical instrumentation was introduced to allow effective cleaning while avoiding excessive removal of sound dentin, which potentially could lead to minimally invasive endodontic treatment.

The purpose of this review is to look at the targets and challenges for effective cleaning of root canals and

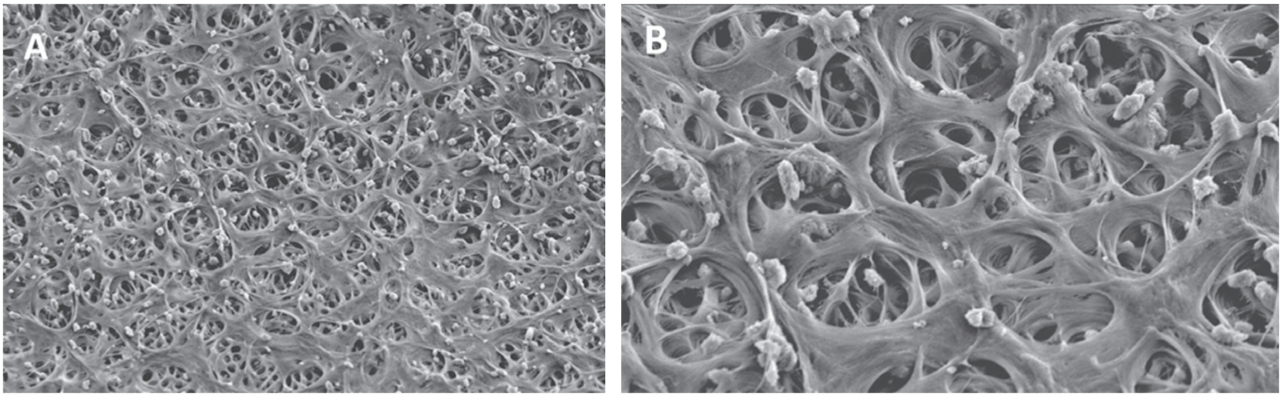

Fig. 1. Canal surface at high magnification. (A) SEM image of the superficial layers of predentin, viewed from the direction of the root canal (original magnification 500×). (B) Higher magnification of "A" (original magnification 1,500×). Adapted from Haapasalo et al. (213).

the means for evaluating the cleaning efficacy and also to evaluate the role of mechanical instrumentation in effectively cleaning root canals.

The targets of cleaning of root canals

Canals with vital pulp

In canals with vital pulp, the aim of cleaning the root canal is to remove the pulp tissue and all remnants attached to the canal walls. Remaining pulp tissue may (i) prevent effective obturation of the root canal and (ii) serve as a potential site for bacterial growth if bacteria reach it, either during root canal treatment or when leakage occurs at a later stage. Given the complex anatomy of many root canals and the nature of the canal surface as observed at high magnification (Fig. 1), this target may be far from trivial and rather difficult to reach in many cases (19–23).

Infected canals: bacterial biofilm

In infected root canals, the target of cleaning is to remove the necrotic pulp tissue and eliminate the infection by removal of the bacteria (8,24). This task is rather challenging. Bacteria that reside in infected root canals tend to grow as a biofilm (25,26). While planktonic bacteria may be easily washed out by irrigation and are rather sensitive to antibacterial irrigants such as sodium hypochlorite, bacteria that grow in biofilms are not as susceptible to these measures (27–30). Bacterial biofilms tend to intimately attach to canal walls (Fig. 2), and simple irrigation is unlikely to remove them. Furthermore, bacteria that grow in biofilms are often more resistant to antibacterial agents such as antibiotics, calcium hydroxide, and chlorhexidine (31–35). This resistance could be from protection by the outer layers of bacteria and the matrix of the biofilm, but also from the biofilm environment that may induce a change of phenotype in certain bacteria and enhance transfer and exchange of genetic information. This may potentially lead to the formation of resistant bacterial strains (36,37).

From the above, simple irrigation of the canal with an antibacterial solution such as sodium hypochlorite, with its relatively high surface tension, may not be as effective as expected in the removal of bacteria from the root canal or in the killing of them.

Infected canals: infected dentin

Dentin tubules in infected root canals tend to be populated with bacteria (38–40). The incidence of bacterial growth in the tubules close to the infected root canal space is the highest (41). Nevertheless, bacterial penetration to depths of 500 μm and even all the way to the cementum layer has been reported (42,43). The optimal target of cleaning would be to remove all of these bacteria, but because this is not practically possible, the common target is to remove the inner, heavily infected layers of the dentin. Additionally, it is desirable to expose the bacteria in the tubules to antibacterial agents. This exposure may be

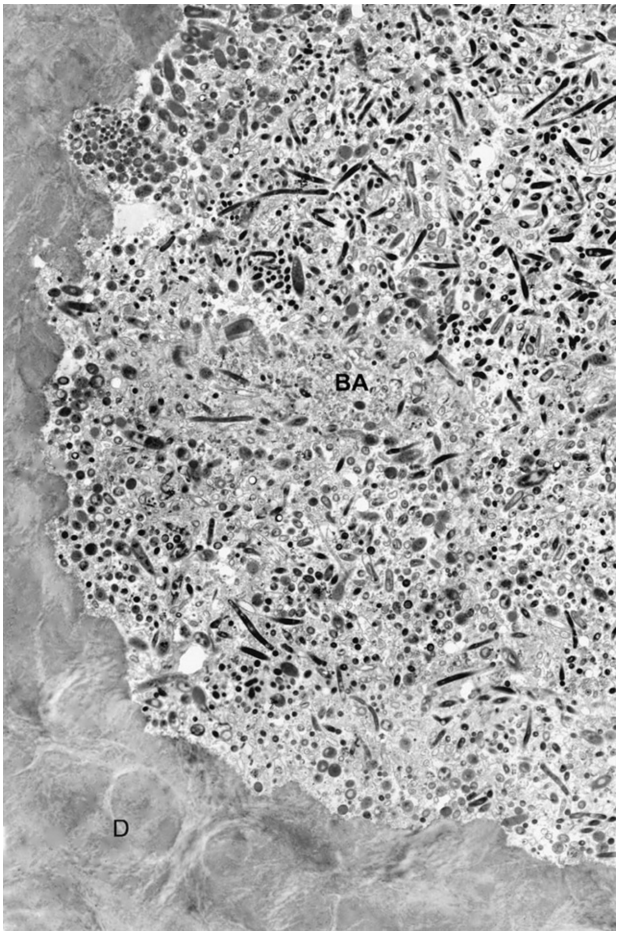

Fig. 2. Bacterial biofilm intimately attached to canal wall. Intimate adaptation of bacterial biofilm to the dentin wall in an infected accessory canal of a mesial root of a mandibular molar. D: dentin; BA: bacteria. Transmission electron microscopy, original magnification 3,200×. Adapted from Nair et al. (25).

better accomplished by removing the smear layer, thus exposing the openings of the tubules to allow antibacterial agents to penetrate as far as possible (44).

Re-treatment

The target for re-treatment of failing endodontic cases is the same as that for root canal treatment of infected root canals. Initially, one has to remove all root filling material, including gutta-percha as well as sealer remnants. Any remaining material attached to the canal walls may prevent effective removal of bacteria and effective removal of the inner heavily infected layer of dentin and limit the exposure of the opening of the dentinal tubules to antibacterial agents.

The challenges of cleaning of root canals

Narrow straight canals

Straight and narrow root canals with a round cross-section can be cleaned by most root canal instrumentation and irrigation systems. Mechanical instrumentation with rotary files will usually include most or all of the canal wall within the circumference of the final preparation, thus mechanically removing from the root canal pulp tissue and bacterial biofilm attached to the canal walls. Most of the cleaning is done in such cases by the mechanical action of the file, and the irrigation is used only to remove debris and smear layer.

If all canals were narrow and straight and had a round cross-section, the challenge of cleaning could be simply and easily met by almost any endodontic protocol. Nevertheless, this is not the case, and many root canal systems differ substantially from this simple configuration.

Flat-oval canals

Flat-oval canals are canals with a long-to-short diameter ratio of 2.5 or larger at 5 mm from the apex. Such canals are found in 25% of teeth, and in certain types of teeth, they may be present in up to 90% of the cases (45). Although this has been well established, such teeth are often subjected to cleaning and shaping methods that are suitable for simple canals with round cross-sections. Most of these methods leave much to be desired in the case of flat-oval canals (14,46–54). It is likely that the similar appearance of these two distinct types of canals in bucco-lingual periapical radiographs leads many dentists to treat such root canals as if they were the same. Cone beam computed tomography (CBCT) scans show the differences clearly (Fig. 3).

Rotary file systems, which are highly effective in cases of simple root canals with a round cross-section, cannot be expected to perform as effectively in the case of flat-oval canals (48–54). The mechanical action of the rotating files is unlikely to affect the entire circumference of the root canal. Uninstrumented buccal and/or lingual recesses ("fins") are consequently a common finding (48–50,53,55). Attempts to overcome this challenge in oval canals by

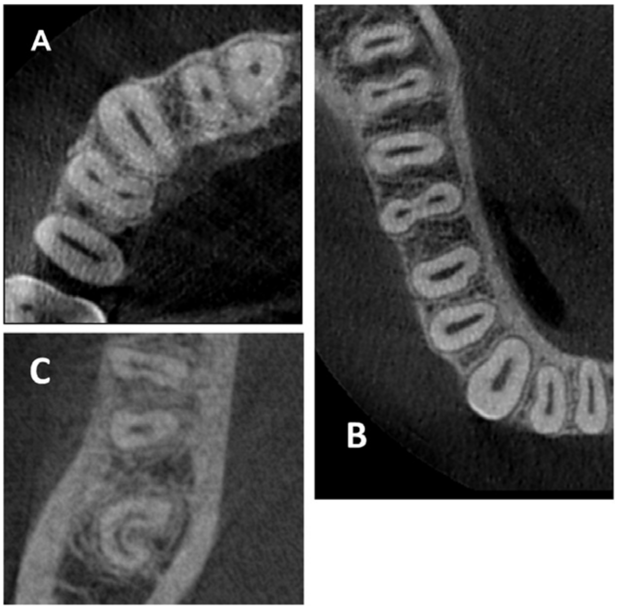

Fig. 3. Flat-oval and C-shaped canals. CBCT axial view of (A) maxilla and (B) mandible reveal the flatness of root canals. Since the flatness is in a plane parallel to the X-ray beam of conventional intraoral radiographs, it is unlikely to be seen in periapical radiographs. Adapted from Metzger et al. (75). (C) CBCT axial view of a C-shaped canal, an extreme case of a flat-oval canal. Courtesy of Dr. M. Haapasalo, Vancouver, Canada.

"brushing" or circumferential filing with rotary files are not effective: a high percentage of the canal wall is still untouched by the files (14,51). This result may be explained by the tendency of the flexible rotary NiTi files to remain centered in the canal. An additional circumferential filing with more rigid hand stainless-steel (SS) files may help to improve, to a certain extent, the mechanical preparation of such flat-oval canals.

Awareness of the above limitations of rotary instrumentation often leads to the adoption and application of the concept that "the file shapes; the irrigant cleans." This concept is applied with the assumption that the sodium hypochlorite will dissolve any pulp tissue or bacterial biofilm contained in these uninstrumented recesses. Such cleaning by chemical action of the irrigant alone, however, is not likely to occur (48,49,53,54,56).

This lack of effective cleaning may be explained in part by the packing of dentin particles and debris into uninstrumented recesses that is caused by rotary files (see below). This packing may make the pulp tissue or biofilm in these recesses inaccessible to the action of sodium hypochlorite.

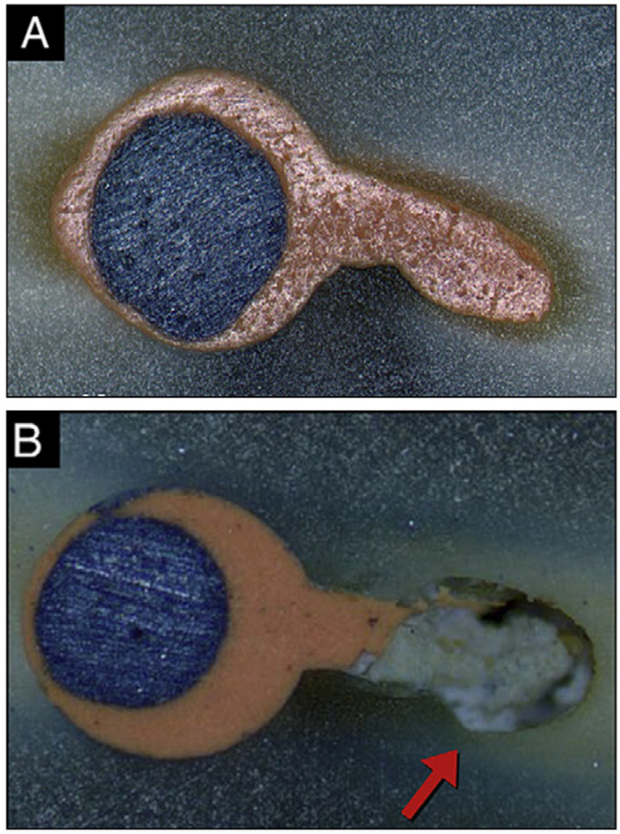

Fig. 4. Adequate obturation of flat-oval canals prevented by debris. Pair-matched flat-oval canals were instrumented with either (A) self-adjusting file with continuous irrigation or (B) rotary files with syringe and needle irrigation. Obturation was done with Thermafill with no sealer. Debris left in the recess in "B" (arrow) prevented the flow of thermoplasticized gutta-percha into the "fin." The clean canals in "A" allowed the gutta-percha to flow into and fill the "fin." Adapted from De-Deus et al. (54).

In a series of studies, De-Deus and co-workers (48,49,53,54) showed that the application of rotary files combined with syringe and needle irrigation with sodium hypochlorite often fails to clean the buccal and/or lingual "fins" of oval canals. Such procedures left the uninstrumented recesses with abundant debris that prevented adequate obturation of the canals (Fig. 4). These findings led De-Deus et al. (53) to conclude that the notion that "the file shapes; the irrigant cleans" represents wishful thinking rather than an accurate outcome, at least in the case of oval canals (53).

Curved canals

Curved root canals of maxillary molars were extensively studied by Peters and co-investigators (57–59). When curved canals were instrumented with rotary NiTi files, 40–50% of the canal wall remained unchanged by the instruments (58,60). This limited ability to touch the entire canal walls was due to a tendency to straighten curved canals, and consequently (i) areas in the outer side of the curvature in the mid-root region and (ii) areas in the inner side of the curvature in the apical part of the canal were not cleaned by the files (58). The oval cross-section of some of the curved canals of maxillary molars may also have contributed to the above limited ability of rotary files to reach all of the canal surfaces (61).

Isthmuses

Roots that have an external oval cross-section usually contain either a flat-oval canal or two canals, which may often be connected to each other by an isthmus (62–64). Effective cleaning of such isthmuses is difficult, and most cleaning and shaping procedures fail to reach these challenging areas (25,65). Nair et al. (25) and Riccuci & Siqueira (65) have shown that neither the use of NiTi files nor the use of SS files could render isthmuses free of biofilm. Furthermore, neither sodium hypochlorite and EDTA nor an inter-appointment dressing with calcium hydroxide can predictably clean these areas of bacterial biofilm (25,26,65).

C-shaped canals

Cleaning of C-shaped canals presents a difficult challenge (66,67). These canals are severe examples of flat-oval canal morphology and have high variability. Some of these teeth will have single ribbon-like C-shaped canals that extend from the coronal orifice to the apex, while others have two distinct ribbon-like root canals (Fig. 5) or even extensive fins or large web-like isthmuses connecting the individual root canals with changing configurations along the length of the roots. This complex anatomy may lead to situations in which hand and rotary files leave up to 66% of the area uninstrumented (67).

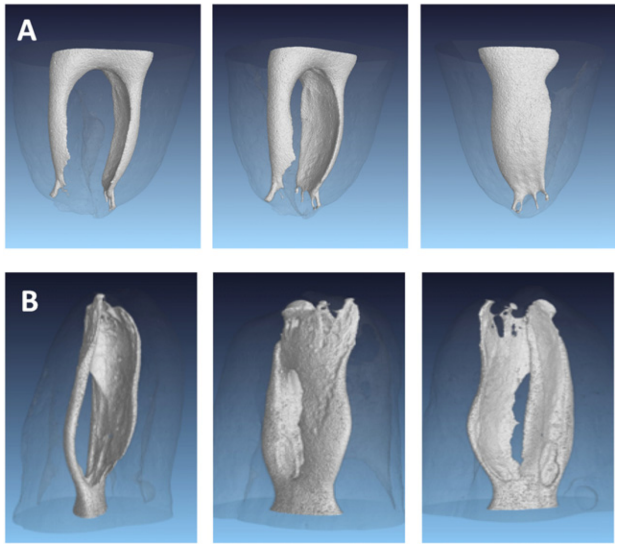

Fig. 5. The challenge of C-shaped canals. (A) C-shaped root canal system of a mandibular second molar viewed from three angles. (B) C-shaped root canal system of a maxillary second molar viewed from three angles. Note the extremely flat root canals. Three-dimensional reconstructions from micro-CT scans. Adapted from Solomonov et al. (67).

Recesses packed with dentin chips by rotary instrumentation

It has recently been demonstrated that rotary files tend to pack dentin chips into isthmuses and potentially into other lateral irregularities of canals (23,49,68–70). In canals with a round cross-section, the dentin chips and debris are either carried coronally by the flutes of the file (71–73), or are compacted into the flutes, as in the case of reciprocating NiTi files. When a lateral space such as an isthmus is present along the canal, the rotating file is likely to pack the dentin chips and debris into this space. This phenomenon was first recognized by Paqué et al. in 2009 using micro-CT (23). When mesial roots of mandibular molars were instrumented with rotary files, the radiolucent space of the isthmus turned radiopaque and disappeared after instrumentation (Fig. 6), caused by packing dentin chips into this space (23).

A similar phenomenon was also demonstrated by Nair et al. (25) using transmission electron microscopy (TEM). Apical segments of mesial roots of mandibular molars that were treated with rotary files and syringe and needle irrigation were surgically removed immediately after the procedure. Histological and TEM examination of these root segments revealed

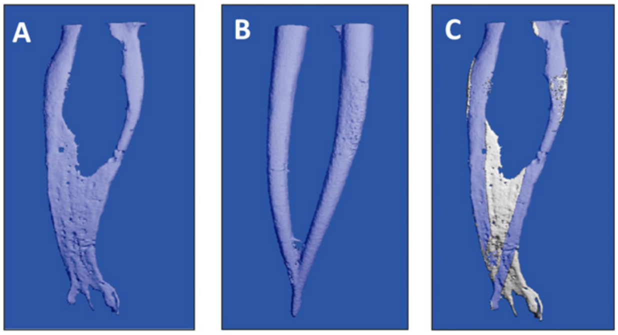

Fig. 6. Packing of isthmus with dentin particles. A micro-CT presentation. (A) An isthmus-containing root canal systems of a mesial root of a mandibular molar. (B) After treatment with rotary files. Note that the isthmus disappeared. (C) White: the isthmus that disappeared by packing radiopaque dentin particles into it by the rotary instrumentation. Adapted from Paqué et al. (23).

both intact bacterial biofilm in the isthmus space and dentin particles that were packed into it (Fig. 7).

It should be kept in mind that the dentin particles are actually packed into either pulp tissue or bacterial biofilm that is present in the isthmus, thus forming a composite structure that is difficult to remove (68,69). A high percentage of these packed particles cannot be removed by syringe and needle irrigation with either sodium hypochlorite or EDTA (68,69). Furthermore, even passive ultrasonic irrigation failed to remove all such packed radiopaque material; 50% of it was still retained in the isthmus even when this effective irrigation method was used (69).

It seems that such a debris packing effect is common to many if not all single-shaft rotary file systems due to their mode of action. Recently it was shown that the reciprocal single files packed greater amounts of debris laterally into isthmuses and recesses than full rotating files (49,70). However, a recently introduced non-single-shaft instrument, the self-adjusting file (SAF, see below), which operates with a completely different mode of action (50,74,75), is almost free of this phenomenon (69).

The phenomenon of laterally packing dentin chips and debris was originally observed in isthmuses. However, it is also likely to occur in any root canal with lateral recesses. Studies to test this last statement are needed.

Lateral canals

Lateral canals are mostly inaccessible to most current cleaning and shaping methods (4,65). As far as vital cases are concerned, such canals may not present a major problem (65). Nevertheless, in infected cases, the pulp tissue in lateral canals may also become necrotic and contain bacterial biofilm that may persist and potentially lead to endodontic failure (76).

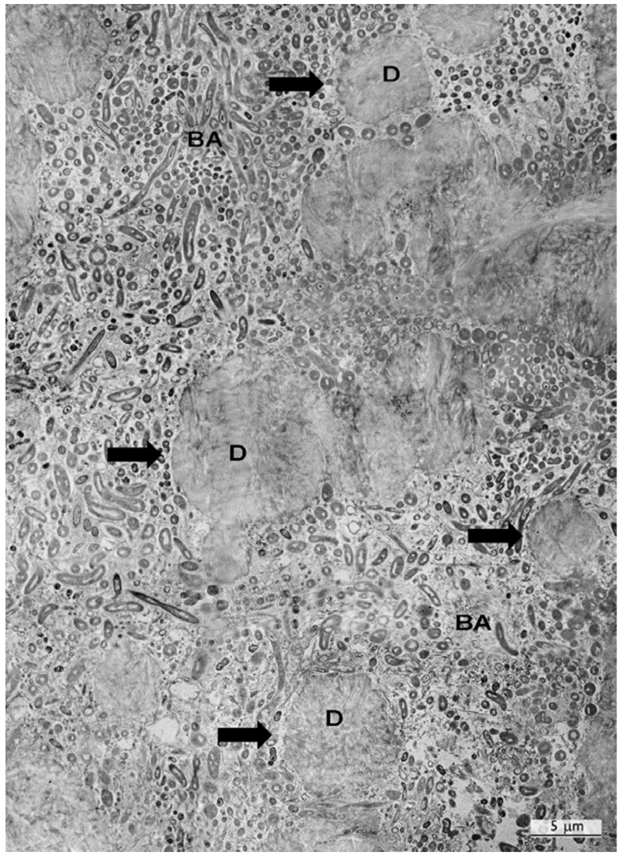

Fig. 7. Dentin particles packed into bacterial biofilm in an isthmus. An isthmus, in a mesial root of a mandibular molar, retained bacterial biofilm after root canal treatment with rotary files. Note the dentin particles (arrows) that are embedded in the biofilm. D: dentin; BA: bacteria. Transmission electron microscopy, original magnification 3,200×. Adapted from Nair et al. (25).

The ability of irrigants such as sodium hypochlorite to penetrate into these lateral canals may be limited by the high surface tension of this solution. Such penetration may be further limited by the presence of debris and smear layer "plugs" that tend to block the entrance of these lateral canals. Instrumentation and irrigation procedures that effectively eliminate debris and the smear layer (77–79) are therefore likely to result in a more frequent radiographic appearance of lateral canals filled with sealer (80) (Fig. 8).

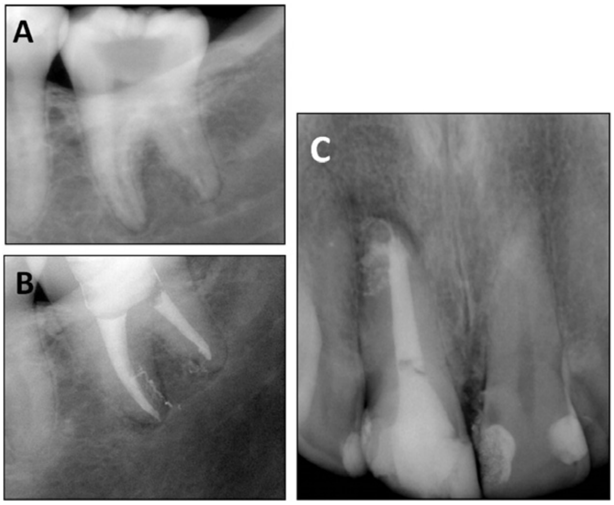

Fig. 8. Lateral canals filled with sealer. The canals of a second left mandibular molar (A) were instrumented and cleaned with the self-adjusting file system, then filled with AH Plus and gutta-percha using a combination technique (80). (B) Sealer entered a lateral canal, most probably due to removal of the smear layer plug or debris in its orifice. Adapted from Solomonov (80). (C) Right maxillary central incisor with an exceptionally wide and oval canal was cleaned and shaped with the self-adjusting file system, then filled with AH Plus and gutta-percha using the System B continuous wave obturation method. Note the sealer emerging from apical ramifications of the root canal.

Apical cul-de-sac areas

The apical area of a root canal preparation represents a cul-de-sac from which biofilms, instrumentation debris, and smear layer are difficult to remove (22,81–83). Most scanning electron microscopy (SEM) studies aimed to evaluate the cleaning efficacy of various instrumentation and irrigation protocols indicate that after completion of the procedure, the apical part of the canal often contained an abundant amount of debris and was covered with a smear layer (22,81–83).

Immature teeth with open apices

Immature teeth are often characterized by apically divergent canals and thin walls (84). The diameter of the canal may exceed 1.5 mm. The instrumentation procedure for such canals differs substantially from that of mature teeth (85). Aggressive filing, which may reduce the thickness of the remaining radicular dentin, is contraindicated as it may predispose the teeth to root fracture (86). The challenge in cleaning such root canals is to remove all tissue debris and bacterial biofilm without compromising the integrity of the tooth. Due to the diverging canal walls, rotary instrumentation with flexible NiTi files is ineffective and cleaning of the canal is largely dependent on the action of the irrigant. The effective use of hand files in apically divergent canals requires dexterity and moderation.

A negative pressure irrigation system (EndoVac, see below) may be useful as it can reduce the risk of a sodium hypochlorite accident. Passive ultrasonic irrigation and sonic activation (see below) may also be applied in these cases. Scrubbing the walls with a self-adjusting file (see below) with continuous irrigation through the hollow file may be another alternative.

Re-treatment

The use of stainless-steel hand files and rotary nickel–titanium files in re-treatment has been intensively studied (87–96). Rotary files can remove the bulk of root filling material quicker than stainless-steel hand files (96,97). Nevertheless, a substantial amount of root filling residue is often left attached to the canal walls after the use of either type of instrument (95,96,98,99). Cleaning this residue may require the use of thicker rotary files, which may (i) transport curved canals (100), (ii) increase the risk of micro-cracks in the radicular dentin (101,102), and (iii) decrease the strength of the root by the excessive removal of sound dentin (13). However, even such excessive enlargement with rotary files cannot guarantee the effective removal of root filling remnants, especially in oval canals (103,104) or curved canals (105).

The common method of evaluating the efficacy of cleaning the root canal by radiographs is of only limited value (96). However, the use of an operating microscope for such evaluation, which is more reliable (96), may be effective only as far as a straight canal is concerned, while being of no use beyond a curvature of the canal.

Evaluation of cleaning efficacy of root canals

Histological criteria

Histological sections, viewed at high magnification, are apparently the best method for evaluating the

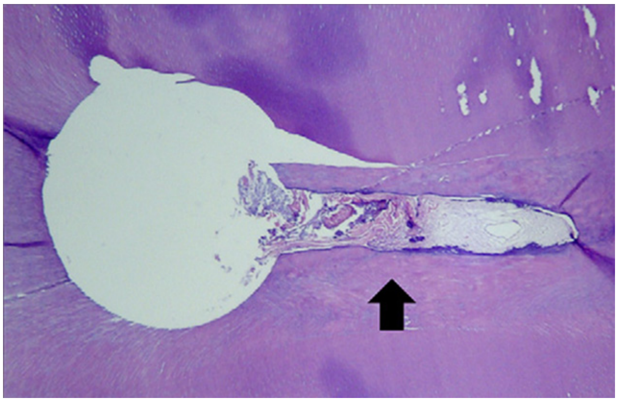

Fig. 9. Histological section used to evaluate cleaning of the canal. Flat-oval root canal with *vital pulp* was treated with rotary files and syringe and needle irrigation. Note the uninstrumented "fin" in which intact pulp tissue is seen in the part far from the instrumented area and the debris, including dentin chip, that clogs the entrance of sodium hypochlorite to the uninstrumented part (arrow). Adapted from De-Deus et al. (53).

cleanliness of the canal wall. Such sections can reveal the nature of the instrumented surface of the canal and show whether a layer of dentin was removed as well as disclose any pulp tissue or bacterial biofilm that remained attached to the canal wall after the cleaning and shaping procedure (Fig. 9) (53).

Nevertheless, such findings are always dependent on the selected plane of sectioning. If each and every root/root canal could be subjected to complete serial sectioning and every section were processed and examined and the evaluations compiled, the result would have represented the true efficacy of cleaning. Unfortunately, such studies are extremely difficult to perform and the costs and time required consequently limit the number of samples that can be used. Histological examination is also subjected to examiner interpretation and often results in semi-quantitative data.

SEM criteria

The efficacy of root canal cleaning has often been evaluated by scanning electron microscopy (SEM) (22,81–83). This method allows evaluation of the amount of debris that is present in each part of the canal (22,81–83). When used at a higher magnification of 1,000×, the amount of smear layer that is present after the completion of the procedure can also be evaluated (Fig. 10) (77,81,83).

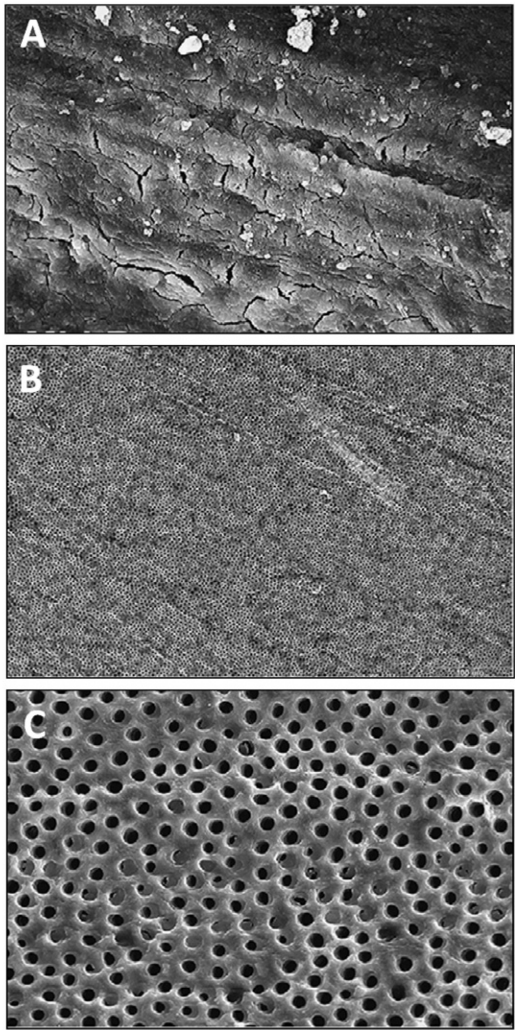

Fig. 10. SEM evaluation of cleaning of root canal. (A) SAF instrumentation with sodium hypochlorite alone: canal surface covered with smear layer (original magnification 1,000×). (B) SAF instrumentation with sodium hypochlorite followed by EDTA: canal surface free of debris (original magnification 200×). Same as "B" at 1,000× magnification: canal surface free of smear layer. Adapted from Metzger et al. (77).

Apparently, this method could be the gold standard for the efficacy of cleaning of root canals. Nevertheless, the evaluation of SEM results is semi-quantitative and is liable to be subjected to (i) potential bias in selecting the field for high power magnification and (ii) variations in observer interpretation of the results. It also requires splitting the root to open the canal for observation, which is rather difficult to perform reproducibly when thin and/or curved roots are concerned.

An interesting approach to overcome the SEM sampling issue was recently demonstrated by Lin et al.

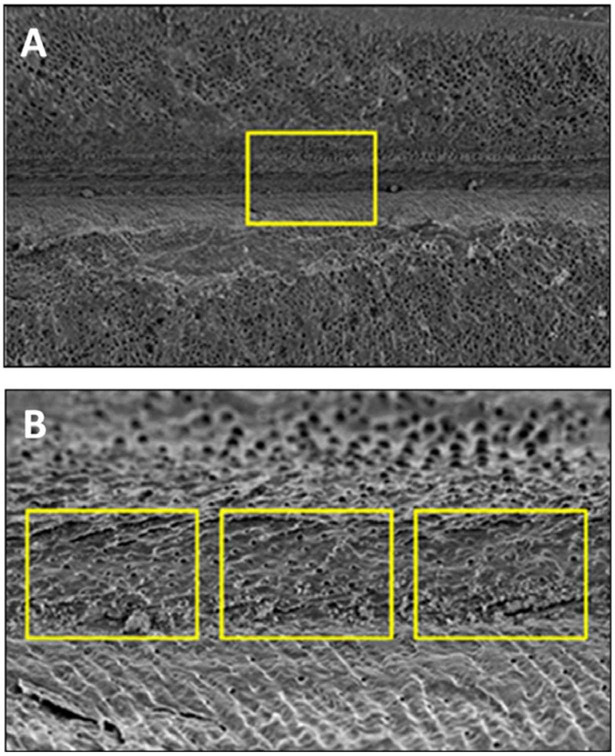

Fig. 11. A groove of pre-determined size used for SEM evaluation of cleaning of recesses. (A) The groove at 100× magnification. (B) The groove at 500× magnification. Yellow: fields selected for evaluation at higher magnification. Adapted from Lin et al. (106).

(106). Teeth were first instrumented to S2 ProTaper file and then split into two halves. A groove with predetermined dimensions of 0.2 mm wide, 0.3 mm deep, and 3 mm long was prepared in the canal wall, representing a fin or an isthmus. A mixed bacterial biofilm was grown *in vitro* in each half of the split root. The roots were then re-assembled, and cleaning and shaping was applied using various protocols. After completion of the procedures, the split root halves were subjected to SEM evaluation for the presence of bacterial biofilm. This procedure could be performed quantitatively in the groove, which represented a pre-selected and well-defined area for the quantitative evaluation of the cleaning efficacy (Fig. 11).

Micro-CT criteria

Micro-computed tomography (micro-CT) has been extensively used in recent years to evaluate the results of canal instrumentation (51,52,58,107–110). Currently, this method is limited to the evaluation of changes that occurred in the mineralized structure of the root. Micro-CT is a non-destructive method that does not require splitting of the root, and it can thus be applied in any root configuration. It allows for objective computerized three-dimensional evaluation of the entire canal wall and is therefore less subjected to bias by sampling, field selection, and operator interpretation.

The criterion that is most commonly used in such evaluations is the percentage of the canal wall that was affected by the procedure (51,52,58,107–110). This criterion assumes that the ideal result should be that 100% of the canal wall is affected by a given procedure. This criterion may be considered an indirect cleaning criterion: if all canal surfaces were changed by a given instrumentation procedure, one can assume that anything that was attached to this wall, be it pulp tissue or bacterial biofilm, was also removed with the layer of dentin that was removed from the surface (75).

In areas in which a given instrumentation procedure did not remove a layer of dentin, one can assume that cleaning of the wall remained totally dependent on the action of the irrigant. Such cleaning by the irrigant alone may occur in easily accessible areas, but it may be of rather limited efficiency in cases of flat-oval root canals (48,49,53) or isthmuses (25). Furthermore, micro-CT is the most effective method to measure the extent of (i) the active packing of isthmuses and other recesses with dentin chips, which occurs when rotary files are used, and (ii) the efficacy of irrigation methods that attempt to remove such debris (68,69). Nevertheless, micro-CT alone is an insufficient method for evaluation of the cleaning of a root canal as it will fail to detect any non-mineralized debris and smear layers present in the canal.

Therefore, it seems that a combination of micro-CT, SEM, and histology may comprise a better combination for evaluation: micro-CT may allow evaluation of the removal of dentin from the entire surface of the canal ***with anything that was attached to it*** while also providing the most comprehensive and objective sampling; SEM may allow for the evaluation of the canal surface for any remaining debris or smear layer on the walls of the canal; and histological examination may yield detailed information on the nature of the instrumented surface and anything that remained attached to it, which only such sections can provide.

Concepts of root canal cleaning

The initial cleaning of root canals is commonly performed by mechanical instrumentation, which removes the large bulk of the root canal content. Such mechanical instrumentation is performed using either hand stainless-steel files or rotary nickel–titanium files, neither of which is expected to completely clean the canal when used alone (21,111,112). Currently, various irrigation techniques and devices are being used together with the mechanical instrumentation to improve the cleaning and disinfection of root canal systems. Irrigation of the canal is usually intermittent and applied after each instrument is used (113).

Recently a new concept of simultaneous mechanical instrumentation and irrigation has been introduced: the irrigant is continuously applied through a hollow file throughout the instrumentation process (50,74,75).

The greatest challenge to all cleaning methods is the effective cleaning of canal fins, isthmuses, and cul-de-sac areas that are often left untouched after the completion of mechanical instrumentation (19,23,46,47,51,59,107,114,115).

Mechanical instrumentation with syringe and needle irrigation

Traditionally, the chemomechanical preparation of root canals has included the use of a conventional endodontic syringe and needle for irrigation. This method is the most widely used because it is very easy to manipulate and allows good control of needle depth and volume of irrigant delivered (116–118). However, this method has two major drawbacks related to its safety and its efficacy (46,54,119–122).

The safety of this method has been questioned because of the positive pressure used to introduce the irrigant into the canal, which can sometimes extrude the solution periapically, resulting in severe tissue damage and postoperative pain (119,120).

Cleaning efficacy studies have also shown that conventional syringe and needle irrigation leaves a large amount of debris clogged in the irregularities of the root canal system (46,48,54,121,122), and does not efficiently deliver the irrigant solution into the apical third of the canal (123). Hsieh et al. (124) used thermal image analysis to record fluid distribution during irrigation in extracted teeth. They demonstrated that irrigation was improved by a more apical placement of the needle tip and by the larger size of the canal preparation (124). Several studies have shown that the irrigant solution does not travel more than 1–1.5 mm deeper into the canal than the needle tip (125–128). Nevertheless, Munoz & Camacho-Cuadra (123) found, in an *in vivo* study, that even when the needle was placed 2 mm short of the working length (WL), the irrigant solution only penetrated 0–1.1 mm deeper than the tip of the needle (123).

The inability of the irrigant to penetrate is likely to be due to the vapor lock phenomenon. The vapor lock phenomenon occurs when there is air entrapment at the end of a closed-end channel, such as the root canal enclosed in the surrounding bone (125). Even side-vented needle irrigation, which has been proposed to improve the hydrodynamic action of irrigant flow, has been found to be ineffective in flushing debris from the apical third of the canal (125).

Furthermore, many root canals present with apical curvatures, thus making placement of the irrigation needle 1 mm short of the working length almost impossible. Shen et al. (129) used computed fluid dynamics (CFD) and Gulabivala et al. (130) used fluid mechanics analytical modeling to demonstrate that the flow of irrigant in immediate contact with the canal wall was practically zero in not only the apical area but throughout the root canal, explaining the limited ability to flush out debris and bacterial biofilm (129,130).

Mechanical instrumentation with negative pressure irrigation

Negative pressure irrigation was developed to address the limitations and risks associated with positive pressure irrigation, such as that of extrusion of the irrigant and the difficulty in delivering to and replenishing the irrigant in all parts of the root canal, especially the apical third (116,126,131,132). This technique has been introduced to the commercial market as the EndoVac system (SybronEndo, Orange, CA). This irrigation system consists of a master delivery/suction system, macro-cannula, and micro-cannula that are connected to a vacuum line (132).

When using this system, the irrigant is delivered into the pulp chamber with the master delivery tip and is pulled into the apical part of the root canal by the negative pressure that is created at the apical part of the macro-cannula or micro-cannula (132,133). The EndoVac system has been shown to achieve significantly better irrigant penetration when compared to conventional syringe and needle irrigation (133). The negative pressure exerted by the macro-cannula or micro-cannula allowed the irrigant to penetrate almost all the way to the working length (WL). The EndoVac system was also significantly more effective than conventional syringe and needle irrigation in removing debris from the apical third of root canals at 1 mm short of the WL (125,132), but it did not perform better at 3 mm short of the WL (122,133).

The major advantage of negative pressure irrigation is the elimination of the risk of irrigant extrusion, even when inserting the micro-cannula at full working length (120,134,135). Nevertheless, it was shown that the negative pressure irrigation system was less effective in reducing bacterial counts when compared with passive ultrasonic irrigation (PUI, see below) (136). Additionally, even after the negative pressure irrigation system was used, debris still remained in the apical 1.5 mm of the root canal (137).

The recommended canal preparation for the use of the EndoVac system is 40/0.04 or 40/0.06 (138,139). Such preparation is not always possible in thin curved canals/roots. Clogging of the 12 0.1-mm holes on the apical end of the micro-cannulae is another limitation encountered in this system (140).

Mechanical instrumentation and passive ultrasonic irrigation

Passive ultrasonic irrigation (PUI) has been introduced to increase the effectiveness of canal cleaning and disinfection by ultrasonic agitation of the irrigant solution inside the canal. After completion of mechanical preparation, PUI can be used in either the continuous or intermittent mode. In the intermittent technique, the canal is first filled with the irrigant and a special ultrasonic tip (141,142) or a size 15 or 20 ultrasonic file is activated in the canal up to 3 mm from the working length (143). The ultrasonic tip is moved passively with an in-and-out motion to ensure that it does not bind with the root canal walls (144). The recommended activation protocol is three activation cycles of 20 s each per canal (145,146). The MiniEndo™ handpiece (Spartan EIE Inc., San Diego, CA) represents a new approach in PUI in which continuous irrigation with PUI is applied for 1 min per canal (147). It has been shown that PUI is significantly more effective at reducing bacterial counts from the root canals when compared with conventional syringe and needle irrigation, although it does not completely eliminate all bacteria from the root canals (148,149).

Ultrasonic activation of the irrigant by an oscillating file creates acoustic micro-streaming and cavitation that push the irrigant laterally into the irregularities of the canal. Thus, the irrigant can access areas that were not touched by the instruments and are hardly ever reached by the irrigant when used in other modes, due to the high surface tension of the irrigant (144,150,151). Consequently, PUI provides better cleaning of the root canal system (117,152). It has also been reported to allow better penetration of the irrigant into lateral canals (153,154) and into narrow isthmuses (155) compared to syringe and needle irrigation. Greater penetration of the irrigant into dentinal tubules has also been reported, even at 1 mm from the working length (156).

The cavitation effect produced by PUI combined with the increase in irrigant temperature by the intermittent technique also resulted in better tissue dissolution (144,157). Nevertheless, in spite of all of these relative advantages, there was no difference in the mean percentage of cleanliness after the irrigation of plastic root canal models when comparing syringe and ultrasonic irrigation methods (158), and there was also no significant difference when comparing them for their antibacterial efficacy against *Enterococcus faecalis* in root canals (159).

PUI performs best in large and straight canals (141,142,145). When used in narrow and/or curved canals, an inherent technical problem of PUI is often observed: contact of the ultrasonic file with the canal wall results in the abolition of the PUI effects and may result in ledge formation (160,161).

Mechanical instrumentation and sonic activation of the irrigant

Sonic irrigation operates at a lower frequency (1–6 kHz) than ultrasonic irrigation (20–26 kHz). It produces smaller shear stresses (150) and generates significantly higher amplitude, resulting in vibration that has been shown to be efficient for root canal debridement (162). The EndoActivator (Dentsply

Tulsa Dental Specialties, Tulsa, OK) is a sonically driven canal irrigation system (163) that was reported to be able to effectively clean debris from lateral canals, to remove the smear layer, and to dislodge clumps of simulated biofilm within curved canals (164). Nevertheless, studies by Stamos et al. (165) and Jensen et al. (166) reported that even though the sonic instruments may contribute to the cleanliness of the root canal, they still leave residual debris on the canal walls in hard-to-reach locations.

Self-adjusting file with simultaneous irrigation and scrubbing

The self-adjusting file (SAF) system (ReDent, Raanana, Israel) represents a new concept in root canal cleaning (50,74,75,77). It is based on using a hollow file that adapts itself to the shape of the canal, rather than the common concept of shaping every canal to a round cross-section (50,74). The file is built as a hollow compressible cylinder, made of a nickel–titanium lattice with a rough external surface (74). It removes a uniform layer of dentin all around the perimeter of the root canal; thus, a round canal is enlarged to a larger round canal, but a flat-oval canal is prepared to a flat-oval shape of larger dimensions (50,52,110) (Fig. 12).

The hollow file allows continuous irrigation through its lumen; thus, irrigation occurs continuously and simultaneously with instrumentation (50,75,167). The SAF system is operated with a peristaltic pump (VATEA, or Endostation, ReDent) that delivers the irrigant into the file through a polyethylene tube attached to a special rotating hub on the file.

In contrast to methods of positive or negative pressure irrigation, the SAF system may be described as a no-pressure irrigation system. The walls of the file are made as a lattice structure; therefore, any pressure generated by the peristaltic pump is immediately released when entering the file. Delivery of the irrigant by this system, all the way to the apical part of the canal, involves no pressure (74,75).

Delivery of the irrigant to the apical part of the canal occurs via a combination of the in-and-out vibration of the file (74) and the continuous pecking motion to working length that is applied by the operator (75). A fresh, fully active irrigant is continuously delivered into the canal, and it is fully exchanged in the apical part of the canal every 30 s throughout the 4-min instrumentation of the canal (75).

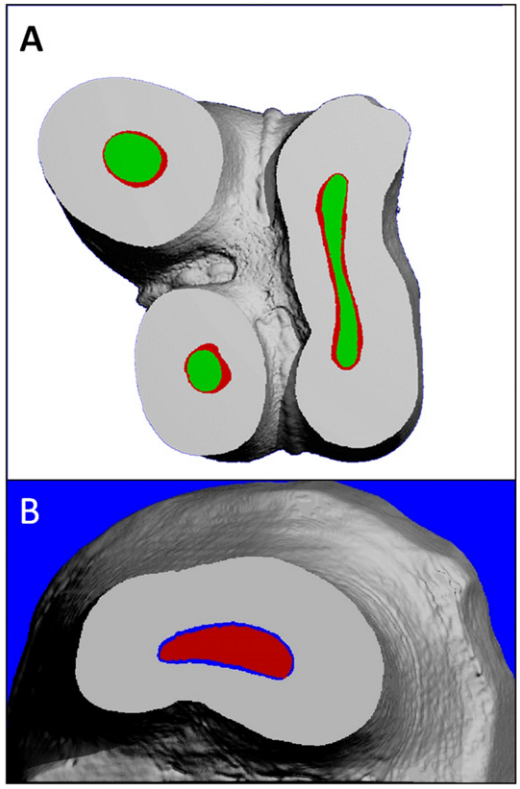

Fig. 12. Removal of a uniform layer all around the canal. Root canals were instrumented with the SAF system. (A) Maxillary molar with extremely flat root canal. Flat canal was prepared as a flat canal, while round canals were prepared as round canals of larger dimensions. Green: the canal before treatment. Red: the layer of dentin removed. Adapted from Solomonov (80). (B) Distal root of a mandibular molar. Red: the canal before treatment. Blue: the layer of dentin that was removed. Adapted from Metzger et al. (50).

Despite the pecking motions to working length, no irrigant is extruded through the apical foramen. This observation is due to the structure of the apical part of the file (74). When fully compressed, the cross-section of the apical part of the file has a square shape that, when applied in a canal prepared with a glide path of a #20 file, leaves 40% of the cross-section free and available for backflow of the irrigant (74,75). This structure allows no piston pressure to develop during the in-and-out motion of the file, as opposed to what is likely to happen when any round file (hand or rotatory) is inserted into the apical part of the canal (74).

Because the metal mesh of the file is closely adapted to the canal walls and is in continuous movement, a scrubbing action occurs, which is most likely the reason for the extremely clean canal surface that has been reported, even in the cul-de-sac-shaped apical part of the canal (Fig. 10) (77–70). Cleaning of the canal by this system is not accomplished by a stream of irrigant but rather by a *scrubbing action* while simultaneously continually replacing the irrigant so that it is always applied as fresh, fully active solution all the way to the apical part of the canal (50).

These results are in apparent contradiction with the results of Paranjpe et al. (168), who found more debris and smear layer in canals treated with the SAF compared to a rotary file used with syringe and needle irrigation (168). The presence of such debris could be explained by the protocol used in their study: 2 min of SAF operation with sodium hypochlorite irrigation, followed by 1 min of SAF operated with EDTA irrigation and another 1 min of SAF operated with sodium hypochlorite. The last 1 min of SAF operated with sodium hypochlorite most likely produced a new smear layer that covered the surface initially cleared of smear layer by the EDTA.

de Gregorio et al. (169) have found that the pecking motion of the SAF was essential for moving the irrigant apically. They concluded that the SAF did not deliver the irrigant to the working length, while the EndoVac system did. This result stands in apparent contradiction with the reported cleaning efficacy of the SAF in the apical part of the canal (78,79). This could be expected as both systems were used in this study for only 30 s, which is greatly different than the full 4 min of operation recommended by the manufacturer of the SAF and applied in previous studies (78,79).

Even though the SAF file assumes the shape of most flat-oval canals, it cannot be expected to mechanically enter recesses, such as certain isthmuses, that are less than 200 μm wide. This limiting factor represents twice the thickness of the SAF file wall (74,167). This limitation could potentially explain the results of a recent study by Siqueira et al. (170), who in a previous study reported that in oval canals, disinfection by the SAF system was superior to rotary instrumentation with syringe and needle irrigation (30), but in the recent study, found no difference between the systems when employed in cases with an isthmus (170). This difference may illustrate an important fact about mechanical instrumentation: in places that are mechanically inaccessible, even for the SAF, the clear benefit seen in oval canals cannot be seen there.

However, the cleaning ability of the SAF was clearly demonstrated in a recent study by Lin et al. (106). They used a new model of a groove full of biofilm, representing an infected recess or fin. Hand files and rotary files that were used with syringe and needle irrigation left 27% and 19% of the groove area covered with biofilm, respectively, while the SAF system reduced the area covered with biofilm to 3% of the groove area (106).

The mode of action of this file prevents the packing of recesses with dentin chips that rotary files exhibit (23,68,110). This lack of packing is due to the mode of action of the file, which does not generate dentin chips and does not involve rotation. Dentin is removed as a thin powder that is continuously suspended in the irrigant and carried coronally with its backflow. Consequently, the access of the irrigant to irregularities is free from obstruction by packed debris and dentin chips (75).

Summary of cleaning concepts

Current cleaning concepts involve mechanical instrumentation of the root canal that removes the bulk of the material contained in the root canal and irrigation systems of various types, which are expected to flush out debris that is left in the canal after mechanical instrumentation and reach places in the canal not reached by mechanical instrumentation and remove remaining tissue debris and/or bacterial biofilm that is left there.

Therefore, in addition to its flushing action, the irrigant is usually required to have the ability to dissolve tissue and to remove the smear layer generated by mechanical instrumentation. The methods by which the irrigant is applied are intended to allow it to reach hard-to-reach areas of the canal. The last is easily achieved in simple straight round canals, but some of the delivery systems such as syringe and needle irrigation often fail to achieve this goal where flat-oval canals are concerned.

The role of mechanical instrumentation in cleaning root canals

Mechanical instrumentation of the root canal has a dual goal: (i) allowing effective cleaning of the canal and (ii) producing a shape that can be obturated with a given root canal filling method. The latter is a strictly mechanical goal that has changed over the years. In the 1960s, the desired shape was that of a standardized master cone; currently, the desired shape may be one that will allow the use of thermo-plasticized gutta-percha methods. Nevertheless, it is widely accepted that ***the canal must first be clean*** to allow for the effective use of ***any*** obturation method (171,172).

If remnants of pulp tissue or biofilm are retained along the wall or if an isthmus or a "fin" are packed with debris, no root filling method may allow adequate obturation of the canal (173–176). This situation in turn explains the great emphasis placed in recent years on shaping as a tool to allow for ***adequate cleaning*** of the root canal space.

Removal of the bulk of the root canal content

The first basic role of mechanical instrumentation in cleaning root canals is the removal of the bulk of the material contained in the root canal (171). Such material could be the bulk of the pulp tissue, the necrotic debris and bacterial biofilms, or a previous root filling. Unless this bulk of material is first removed, no further cleaning is possible. Such removal should occur with all instrumentation protocols. Nevertheless, this removal alone does not usually render the canal clean, and various irrigation protocols are used to remove what is left after this initial removal of the root canal content (114,177,178).

Allowing for effective irrigation

Effective irrigation of the root canal is expected (i) to flush out any debris that is present in the canal after mechanical instrumentation, (ii) to dissolve and remove any remaining tissue or biofilm that remained in areas inaccessible to mechanical instrumentation, and (iii) to remove the smear layer generated by mechanical instrumentation. Each and every one of these goals requires the irrigant to reach into the place in which those components are present.

In some wide canals, the removal of the canal content is enough to allow insertion of the irrigation needle all the way to the working length. However, in narrow canals, mechanical instrumentation and enlargement of the canal are often required before the needle can reach the apical part of the canal (126). The condition may be even more complicated in curved narrow canals in which positioning the irrigation needle to the working length presents a greater challenge (179).

The apical size debate

The optimal apical size of a preparation has been extensively debated over the years (6,7,180). The apical constriction is, in theory, the narrowest part of the root canal and the location where the pulp ends and the periodontium begins. The canal at this constriction is not uniformly round but is generally either ovoid or irregular (45). Therefore, if the entire canal wall is to be included within the preparation, an instrument size at least equal to the largest diameter of the apical canal may be required. Morphology studies indicate that the apical canal is often wider than 300 to 350 μm in normal adult teeth and may be even larger when resorption by apical periodontitis has occurred (181,182). The canal anatomy therefore dictates that to include the entire canal wall in the preparation, a minimum apical preparation to size 30 to 35 or larger is required (183).

Microbiological studies have also shown that larger apical preparation sizes produce a greater reduction in remaining bacteria compared to smaller apical sizes (6,180,184–188). As bacteria penetrate into dentinal tubules at variable distances (40,43), larger apical preparations will improve the removal of the more heavily infected inner dentin (189,190). Shuping et al. (186) found that irrigation with sodium hypochlorite improved disinfection of the canals ***only*** *after they were enlarged to size 30–35 or more*. Histological studies have also indicated that increased apical enlargement will lead to cleaner apical preparations as measured by the amount of remaining debris (12,21). In infected root canals, the apical preparation is especially critical and must aim to maximize microbial control (191).

Apical preparation to size 25, which is advocated by some file systems, is unlikely to mechanically affect the canal walls or to even touch them (183). Thus, when such apical sizes are used, cleaning of the apical part of the canal greatly depends on the effect and action of the irrigant.

The effective delivery of an irrigant in the apical part of the canal is dependent on the size of the apical preparation, both in the case of syringe and needle irrigation (116,189) and in the case of negative pressure irrigation (138). When Cohenca and co-workers (138,139) studied the efficacy of the EndoVac negative pressure irrigation system, they found that apical preparations of 40/0.04 and even 40/0.06 were required for the effective use of the EndoVac system.

Apical preparation to size 25 is used with some file systems in spite of the above findings (73,192). The purpose is to reduce the risk of file separation, especially with a single file system, and to allow the use of root canal filling techniques that involve thermoplasticized gutta-percha. Apical control and avoiding apical extrusion of softened gutta-percha dictate a limited enlargement of the apical part of the canal (193,194). The biological goals of optimal chemomechanical debridement of the apical root canal are therefore ignored and compromised to accommodate a certain type of root canal obturation method (187).

The self-adjusting file system represents an attempt to overcome the apical size issue. Rather than attempting to include the entire apical canal circumference within a given round preparation, the self-adjusting file adapts itself to the cross-section of a given canal. If the canal is oval, it is enlarged to an oval canal of larger dimensions (50,74), removing a uniform dentin layer from the entire circumference of the canal (Fig. 12). The issues of needle size and the hydrodynamics of irrigant flow are also bypassed, as no needle is used for irrigation. The irrigant reaches the apical part of the canal by the agitating motion of the file (75) and is applied to the canal walls with a scrubbing action rather than as a flow of liquid over the surface that is to be cleaned. Consequently, it results in a canal clean of debris and often free of smear layer, even in the cul-de-sac apical part of the canal (77–79). Unnecessary removal of sound dentin is also avoided, thus allowing an effective minimally invasive procedure (75).

Re-treatment

When re-treatment is performed in failing endodontic cases, the bulk of the root filling material can be removed using rotary files (195,196). The material that remains attached to the canal walls must be removed to allow for effective cleaning and disinfection of the canal. Such residues need to be removed mechanically as irrigation alone will not be effective. One approach may be to further enlarge the canal with round instruments. This approach has two major drawbacks: (i) the canal has been enlarged in the initial endodontic treatment, and further enlargement may jeopardize the integrity of the root; and (ii) in curved canals, the use of thicker instruments is hazardous. An alternative approach was recently studied: the use of the self-adjusting file, which effectively scrapes the root filling residues without excessive enlargement of the canal that would have otherwise been needed (104,105).

Limiting factors

All evidence indicates that larger mechanical preparation of root canals may facilitate more effective cleaning and disinfection (60,184,185,190,196–198). If so, what are the limiting factors for such an approach?

The first factor is the ***curvature of the canal***. When curved canals are mechanically instrumented, one runs into the risk of transporting the canal, sometimes to the extent of zipping or strip perforation (111,119,193,199,200). While thinner nickel–titanium files are very flexible, thicker instruments, such as those size 30 and larger, are less flexible and cannot be safely used to the working length in curved canals (111,201–204).

The second factor is ***micro-cracks*** in the radicular dentin that may be caused by rotary instrumentation (102,205–211) (Fig. 13). Recent studies indicate that using size 30 or 35 rotary files to the working length resulted in micro-cracks in the apical part of the root in 35% or more of the cases (102,209). Furthermore, re-treatment in such canals further increases the risk of micro-cracks (207).

The new instrumentation/irrigation technology represented by the self-adjusting file system may overcome some of the above limiting factors by applying a “minimally invasive” approach: the traditional round preparations of the root canal are replaced by enlarging oval canals to a similar shape but a larger size, thus allowing effective cleaning with no need for a certain size of apical preparation (77–79). Additionally, the different mode of action of this file substantially reduces or eliminates the occurrence of micro-cracks in the radicular dentin (208,210).

Narrow isthmuses represent another limiting factor, as none of the current technologies can safely, reliably,

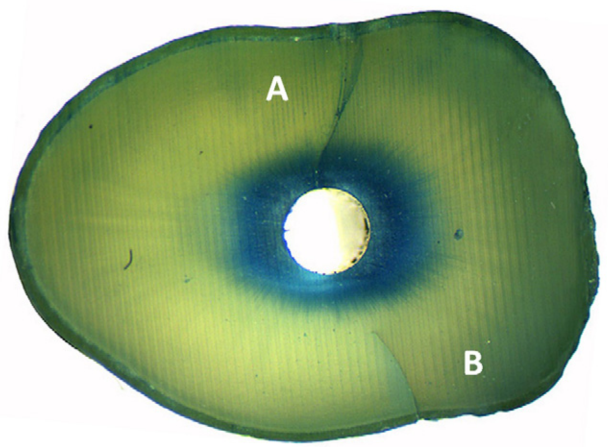

Fig. 13. Micro-cracks in radicular dentin caused by rotary instrumentation. Root canal instrumentation with rotary files. Cross-section at 6 mm from the apex. (A) Complete micro-fracture. (B) Partial micro-crack. Adapted from Bürklein et al. (211).

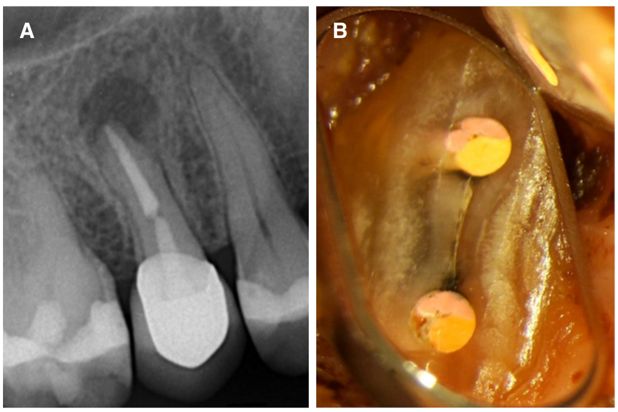

Fig. 14. A narrow long isthmus as a cause for endodontic failure. (A) Radiograph of a right second maxillary premolar revealing a failing endodontic case, in spite of apparently adequate root canal filling. (B) The cause of failure: a long narrow isthmus. Adapted from Metzger et al. (75).

and reproducibly clean them (4,50,212) (Fig. 14). They represent a challenge to mechanical instrumentation in effective cleaning of the root canal system. No existing mechanical instrumentation system can effectively and safely address the narrow isthmuses, and thus they often remain as a cleaning failure, demonstrating the limitations of the irrigant alone as a cleaning method of the mechanically inaccessible places in the root canal system.

Conclusions

The effective cleaning of root canals requires mechanical instrumentation combined with irrigation. As long as the root canal is straight and narrow with a round cross-section, the two can work hand-in-hand and effectively clean the canal. In curved canals or those with an oval cross-section, however, cleaning requires mechanical preparation, which is difficult or even impossible to accomplish with rotary instruments. In such cases, one depends too heavily on the action of the irrigant, which does not always live up to its expectations. New methods that will bypass the limitation of the current technology of cleaning root canals should be sought and adopted.

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