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Irrigation activation methods in endodontics: A comprehensive review

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Abstract

In contemporary endodontics, the core objective is to thoroughly cleanse and disinfect the root canal system. While shaping the canals is an important step, it alone is not sufficient. Successful treatment relies on a combined chemo-mechanical approach, which ensures the removal of organic tissue remnants, microbial contaminants, and their by-products from within the canal space. In this context, flushing the root canals with appropriate irrigation solutions is of great importance. The irrigation solutions used play a critical role in dissolving both organic and inorganic tissues and reducing the microbial load. However, the effect of irrigation can be further enhanced by actively circulating and agitating the solution within the canals. For this reason, activation methods such as ultrasonic or sonic activation systems, negative pressure irrigation techniques, and laser-assisted methods have become widely used in treatment protocols in recent years. In short, successful endodontic treatment is not only achieved by shaping the canal; it is also possible through the correct selection of irrigation solutions, sufficient duration of use, and effective activation. Once these procedures are properly carried out, the root canal system becomes more effectively disinfected, which in turn enhances the likelihood of achieving a successful long-term treatment outcome. This article comprehensively evaluates the activation devices used in today's endodontic practices and the new systems recently introduced to the market in terms of their advantages and limitations. Furthermore, current activation techniques are discussed comparatively, and their contributions to clinical practice and differences in use are debated.

Keywords: Endodontic, irrigation activation, sonic irrigation, passive ultrasonic irrigation, EndoActivator, EasyClean, Ultra X

1. Introduction

The goal of endodontic treatment is to remove bacteria and biofilms from the root canal system and prevent their recontamination. The bacterial load is reduced by shaping and disinfecting the canal, and the few surviving bacteria are sealed off with a good seal. However, mechanical instrumentation alone is insufficient; approximately half of the root canal surfaces may remain untouched, and biofilm and smear layer residues negatively affect treatment success. Therefore, for effective treatment, mechanical shaping, irrigation with disinfectant solutions, and activation of irrigation should be applied together (1).

In the literature, it has been reported that passive application of root canal irrigation solutions alone is not always sufficient for removing the smear layer; however, activating these solutions using various methods significantly increases cleaning efficacy (2). Activation methods include ultrasonic, sonic, negative pressure systems, or laser-assisted approaches, which enable the irrigation solution to penetrate deeper into the root canal system and remain effective even in anatomically complex areas.

Furthermore, it has been demonstrated that the activation of sodium hypochlorite increases this solution's capacity to dissolve organic tissue (3). The acoustic cavitation and microcurrent effects generated during activation reduce the surface tension of the solution, allowing it to penetrate the dentinal tubules more effectively. This results in a more successful removal of both biofilms and necrotic tissue debris.

Ensuring that irrigants come into direct contact with the canal walls is essential for improving their cleaning efficacy. However, because root canal anatomy is typically complex and irregular, relying solely on manual instrumentation and passive irrigation may not be sufficient to deliver the solution to all regions within the canal system. Therefore, activating irrigation increases the contact of the solution in both the lateral and apical regions, providing more effective disinfection.

Today, irrigant activation can be performed using both manual and automatic (machine-assisted) methods to clean the root canal system more effectively and increase the disinfection. Among the different activation methods, manual dynamic activation (MDA), passive ultrasonic irrigation (PUI), and sonic irrigation (SI) are the most commonly used and researched methods. Although each of these methods aims to increase irrigation effectiveness, significant differences in the types of devices used, application times, solution concentrations, and canal anatomies in the studies conducted lead to heterogeneity in the results obtained. Therefore, a holistic approach should be adopted when evaluating existing literature data, and it does not yet appear possible to recommend a specific activation method as a standard for all cases in clinical practice (4).

2. Manual activation

2.1. Conventional Syringe Irrigation (CSI)

Conventional syringe irrigation is a method that has been used for a long time and is widely adopted by physicians. In this technique, the irrigation solution is typically administered through special irrigation needles attached to the syringe. These needles, produced in different diameters, can be used passively or with manual back-and-forth movements. One of the biggest advantages of this method is that the clinician can easily control the amount of irrigant applied and the depth of needle entry into the canal. However, this method also has a significant limitation: it is quite difficult to maintain a constant flow rate of the irrigation fluid and apply it at a standard level (5).

Studies using computational fluid dynamics (CFD) models have detailed the flow behaviors of various needle designs within the root canal. These studies have provided valuable data on parameters such as flow patterns, fluid velocity, shear stress, and apical pressure, helping to better understand how the irrigant is exchanged within the canal and how this contributes to disinfection efficiency (6-8). CFD analyses revealed that open-ended needles increased the fluid flow rate and shear stress in the apical region. This increase contributes to more effective removal of debris and biofilms from the root canal (6). In contrast, closed-tip lateral hole needles primarily direct the flow laterally, which limits irrigant exchange at the apical end of the needle tip (7). These results highlight the importance of needle positioning in the root canal. Placing open-ended needles approximately 2–3 mm from the working length is recommended as the optimal approach to increase cleaning efficiency while reducing the risk of apical extrusion (6).

Open-ended needles operate largely unaffected by changes in flow rate, allowing effective renewal of the irrigant within the canal (7). Even if positioned 2-3 mm back from the working length (WL), they enable effective renewal of the irrigation fluid in the root canal. This creates a high-speed jet in the apex direction, allowing for better displacement of the irrigation fluid in front of the needle and as a result, more effective tissue cleaning is achieved (6). This preference for open-ended needles is also consistent with evidence demonstrating the correlation between needle geometry and flow velocity (9). Placing the needle further away from the WL increases turbulence and delays the exchange of irrigation fluid; however, the apical pressure is lower (7). Therefore, it is recommended that closed-tip needles be placed 1 mm away from the WL and open-tip needles 3 mm away from the WL (6).

Irrigation needles are available on the market in various diameters and lengths and are made from both metal and polymer materials.

These include:

NaviTip™ (Ultradent Products, South Jordan, UT, USA) with open-ended 29G and 30G metal needles (Fig. 1),

Figure 1. NaviTip™ irrigation needles (10).

30G metal double-sided hole closed-tip irrigation needle (Fanta Dental Materials Co. Ltd., Shanghai, China) (Fig. 2), and 31G metal double-sided NaviTip™ SidePort irrigation needle (Ultradent Products, South Jordan, UT, USA) (Fig. 3),

Figure 2. 30G metal double-sided hole closed-tip irrigation needles (11).

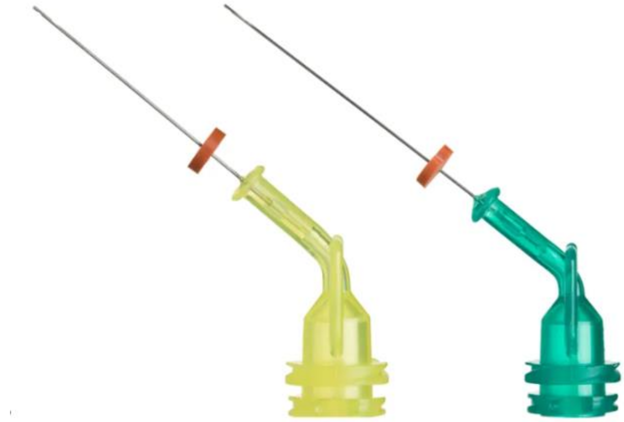

Figure 3. NaviTip™ SidePort irrigation needles (10).

TruNatomy™ (Dentsply Maillefer, Ballaigues, Switzerland) (Fig. 4) and IrriFlex® (PD Dental, Vevey, Switzerland) (Fig. 5), which are 30G polymer needles with a closed tip and dual side vents,

Figure 4. TruNatomy™ irrigation needle (12).

Figure 5. IrriFlex® irrigation needle (13).

Polymer needle tips with diameters of 0.014 and 0.06 inches for irrigation and aspiration: Endo Tips (Angelus, Lindoia, Londrina, PR, Brazil) (Fig. 6).

Figure 6. Endo Tip (14).

Chow et al. conducted a study using 23G and 25G hypodermic needles to evaluate the effectiveness of root canal irrigation. The study findings indicated that smaller-diameter needles provided more efficient irrigation results (15). Guerreiro-Tanomaru and his team examined the effects of different needle sizes (23G, 22G, and 30G) on cleaning the apical third of the root canal. The data revealed that 30G needles were more effective in cleaning the apical region than other needle diameters (16). These findings demonstrate that smaller-diameter needles are superior in terms of apical cleaning during root canal irrigation, and that needle diameter may be a critical factor for effective irrigation.

To achieve the working length even in curved root canals, the use of thin, flexible needles in the 30-31G range is recommended. Currently, the 30G needle is widely accepted as the standard choice in clinical practice (17). With the adoption of more conservative approaches to root canal shaping, it is likely that 31G needles and needles with flexible polyethylene structures will become standard practice in the near future (18, 19).

The intracanal negative pressure (iNP) needle (Mikuni Kogyo Co., Nagano, Japan) was introduced as a successor to the EndoVac irrigation system. This needle has an overall length of 32 mm, with an outer diameter of 0.65 mm and an inner diameter of 0.50 mm. The final 4 mm of the needle was tapered by compressing a section measuring 0.46 mm in diameter, resulting in a tip with an inner diameter of 0.25 mm and an outer diameter of 0.36 mm (approximately equivalent to 28G). The reduced inner diameter at the tip enables efficient delivery of a large volume of irrigant, while the smaller outer diameter permits the needle to be comfortably positioned about 2 mm short of the working length, provided that the canal has been prepared to at least size 40 with a 0.04 taper (20) One study compared the volume of irrigant recovered from the apical third of two different negative-pressure systems under various flow rates. The results of this study showed that the INP needle was able to recover more irrigant from the apical third than EndoVac at all three flow rates used (20).

IrriFlex is a flexible polyethylene irrigation needle with a closed tip and two lateral outlets, developed to improve root canal disinfection. This dual-aperture design allows the high-flow irrigant solution to be delivered in bidirectional, oblique jets, allowing for more effective irrigant circulation across a wider area of the canal and reducing the risk of apical overflow. Due to its 30/0.04 mm diameter, the needle is recommended for use in the apical third, particularly when the canal is shaped to at least 30/0.04 mm, allowing for more effective cleaning and microbial elimination in this area (19).

Silva et al. compared the effects of straight open-tip, side-holed, and double-side-holed needles on the amount of irrigant and debris extruded from the apical region. Their findings indicated that needle design directly impacted the amount of material extruded; in particular, double-side-holed needles significantly reduced apical extrusion compared to other designs (21). Bulgu et al. performed a computational flow analysis to compare the effectiveness of different root canal irrigation needle designs. The analysis revealed that double-sided and closed-tip needles significantly reduced pressure in the apical region compared to open-tip needles. This contributes to increased safety and control during irrigation (22).

In all previously reported cases of sodium hypochlorite extrusion, syringe irrigation using open-ended needles has generally been used (7, 23). These situations have led to serious complications, such as postoperative pain, swelling, tissue necrosis, secondary infection, and permanent paresthesia in some cases. Therefore, irrigation should be performed carefully within the root canal boundaries (24, 25). In this study, the capacity of different needle designs to effectively distribute irrigant throughout the canal and their safety levels were evaluated. Irrigant delivery to the apical region and the risk of irrigant leakage into the periapical tissues are particularly important parameters. Furthermore, it was observed that needles with a smaller diameter reach deeper into the canal, thereby providing more effective irrigant exchange and debris removal (26).

2.2. Endodontic brushes

Brush systems are not intended to serve as devices for delivering irrigating solutions directly into root canals. These instruments are primarily complementary irrigation aids used to mechanically remove debris and smear layer accumulated on the root canal walls and to increase the movement of the irrigant within the canal. However, they can also provide indirect irrigation support by contributing to a more homogeneous distribution of irrigant throughout the canal space. Owing to these functions, brush systems have gained importance in clinical practice, particularly as a supportive element for mechanical debridement. However, due to friction caused by irregularities within the canal, there is a risk of brush bristles breaking off. Since these bristles are radiolucent, there is a risk that they may go unnoticed by clinicians (27).

2.2.1. NaviTip and NaviTip FX brush

NaviTip FX (Ultradent Products Inc, South Jordan, UT); 30-gauge, brush-tipped irrigation needles are designed to indirectly contribute to the delivery of irrigant. However, the use of these bristle tips has shown limited cleaning effect, particularly in the apical and middle thirds of the canal. It is anticipated that this effect could be enhanced by applying inward and outward brushing motions during irrigation. Nevertheless, such maneuvers may cause displacement or deformation of the bristles within the canal, necessitating careful use (28).

Previous studies have shown that NaviTip FX significantly improves canal cleanliness and biofilm reduction compared to traditional syringe irrigation and EndoVac (Fig. 7) (29, 30).

Figure 7. NaviTip and NaviTip FX Tips (31).

2.3. Manual Dynamic Irrigation (MDA)

Manual dynamic irrigation is a technique based on sliding a properly sized gutta-percha point back and forth in 2-3 mm movements within a preformed root canal. This method creates a hydrodynamic effect in the irrigation solutions within the canal, allowing the solution to move along the canal and make more effective contact with the wall surfaces. Consequently, the aim is to achieve a more homogeneous distribution of the irrigant and increased cleaning efficiency in different parts of the canal, including the apical region. Thapak et al. reported that the MDA technique provided markedly better smear layer removal in both the middle and apical thirds of the root canal system than the GSI approach (32).

McGill et al. reported that automated dynamic irrigation with the RinsEndo® device was significantly less effective than manual dynamic irrigation. This result was attributed to the fact that the frequency of the push-pull movements of the gutta-percha cone within the canal in the manual technique (approximately 33 Hz; 100 strokes in 30 s) is much higher than the frequency of the positive-negative hydrodynamic pressure cycles generated by the RinsEndo® system (1.6 Hz). It has been reported that the higher frequency creates stronger turbulence within the canal, increasing the distribution and contact efficiency of the irrigant (33).

Virdee et al. investigated how various irrigation activation techniques influence the ability of sodium hypochlorite to penetrate root dentin. Their results indicated that manual dynamic activation, passive ultrasonic irrigation, and sonic irrigation enhanced the depth of sodium hypochlorite penetration within the dentinal tubules across the entire root canal system, including the apical area, compared with conventional syringe irrigation (34).

3. Activation with the help of machines

3.1. Brushes used with rotating heads

Brush systems developed to support the removal of debris and smear layer formed during root canal treatment were first introduced by Ruddle in 1994 (35). The types currently used commercially are the Endobrush and CanalBrush.

3.1.1. Endobrush

It is a spiral-shaped brush consisting of nylon bristles mounted on bent metal wires, developed for use in endodontic procedures. The Endobrush (C&S Microinstruments Ltd., Markham, Ontario, Canada) system is designed to support the mechanical debridement of root canal walls. In studies conducted by Keir et al. in the early 1990s, the findings indicated that the use of canal brushes could improve canal cleaning. However, because of the structural dimensions of the Endobrush, it is difficult to advance it effectively to the working length, which may increase the risk of debris accumulation in the apical region after brushing. Therefore, although effective cleaning is achieved with the use of the Endobrush, insufficient access to the apical region is considered a potential limitation (36, 37).

3.1.2. CanalBrush

CanalBrush (Coltène Whaledent, Langenau, Germany), which is entirely molded from polypropylene, is extremely flexible and can be used with a manual rotary motion. Weise et al. reported that the use of CanalBrush increases the effectiveness of smear removal from morphological irregularities in the apical regions of simulated lateral canal extensions and inclined root canals (38).

CanalBrush has the potential to mechanically displace medications placed inside the canal, owing to its bristles that come into contact with the canal walls. With this feature, it is considered an effective aid in removing intracanal medications, such as calcium hydroxide [$Ca(OH)_2$]. A study conducted by Markovic et al. showed that CanalBrush significantly improved the removal of $Ca(OH)_2$. However, compared with sonic activation, there was no notable difference in performance. The CanalBrush system was still identified as a useful instrument for the removal of calcium hydroxide (39). Türker et al. reported that the SAF and EndoVac irrigation systems were considerably more successful than CanalBrush in removing calcium hydroxide from the apical third of the root canal. The study indicated that the CanalBrush did not adequately eliminate $Ca(OH)_2$ in this region; instead, it tended to push the material further apically, leading to accumulation at the apex rather than effective removal (40). When these two studies are evaluated together, it is understood that CanalBrush is somewhat useful in removing calcium hydroxide [$Ca(OH)_2$] from the root canal, but its effectiveness varies depending on the irrigation/activation system used and, in particular, the region of the canal.

3.2. Special endodontic files

3.2.1. Self-Adjusting File (SAF) system

The self-adjusting file (SAF) system (SAF, ReDent-Nova, Ra'anana, Israel) is a root canal file made of a nickel-titanium alloy, featuring thin walls, a cylindrical shape, a hollow interior, and high flexibility. Its compressible structure allows it to conform to the canal anatomy. The abrasive structure on the outer surface of the file enables shaping of the canal walls through back-and-forth and vibratory movements, while its hollow design ensures that the irrigation solution is continuously delivered and activated throughout the root canal. It has been reported that this system significantly increases its effectiveness by providing an uninterrupted solution flow during canal preparation (Fig. 8) (41).

If the canal is straight, narrow, or round, most files can adequately achieve their shaping goals. However, when the canal is oval or curved, rotary files, whether the latest or traditional, may be insufficient to address these challenges. The most important factors determining successful root canal treatment are three-dimensional cleaning, shaping, or filling of oval and curved canals, the microbiome of infected canals, and preservation of the integrity of the radicular dentin. The SAF system assists in this regard by providing natural three-dimensional shaping, cleaning, and, in particular, irrigation of narrow, oval, or round-sectioned straight canals, which are often overlooked. It allows for continuous irrigant flow during preparation (43, 44).

Figure 8. Self-Adjusting File (SAF) system (42).

SAF is generally available in two different sizes: 1.5 mm and 2.0 mm, and these files can be compressed quite effectively. The 1.5 mm diameter file (available in lengths of 21, 25, and 31 mm) can be compressed to approximately a 20-gauge K-file size, whereas the 2.0 mm diameter file can be compressed to a size similar to a 35-gauge K-file (45). The 1.5 mm diameter file is designed for canals with an apical size of ISO 20–40, whereas the 2.0 mm diameter file is used for wider canals with an initial apical size of ISO 35–60. Rather than forcibly changing the shape of the canal, it adapts to the original shape of the canal, both longitudinally and circumferentially. The working surface of this file is rough. When inserted into the SAF canal, it compresses and adapts to the canal's cross-section; it takes on a round cross-section in a round canal and takes on that shape in an oval or flat-section canal, providing three-dimensional adaptation by applying continuous light pressure around the entire canal (41, 46).

3.2.2. XP-Endo Finisher (XPF) file

The XP-Endo Finisher (XPF; FKG Dentaire SA, La Chaux-de-Fonds, Switzerland) is a next-generation nickel-titanium (NiTi) instrument developed to enhance irrigation efficiency in complex root canal anatomies. Designed to provide effective cleaning in areas difficult to reach with conventional shaping systems, this flexible, shape-memory instrument adapts to the canal morphology during operation. Owing to the patented MaxWire (Martensite–Austenite–Electropolish–Flex) temperature-sensitive alloy used in its manufacture, it has a 27-gauge tip diameter and a .01 taper in the martensitic phase at room temperature. Upon reaching body temperature (approximately 35°C and above), it transitions to an austenitic phase, expanding to a 30-gauge tip diameter and a .04 taper. According to the manufacturer, the innovative design and special alloy structure of the XPF optimizes mechanical debridement by establishing more effective contact with the canal walls. This feature leaves less uncleaned area on the root canal surface compared to traditional shaping systems (47, 48).

The XPF should be operated at approximately 800 rpm when used with irrigation solutions. It should be applied only after the root canal has been shaped to at least size #25 or larger (Fig. 9a).

3.2.3. XP-Endo Finisher Retreatment file

In recent years, another component of the system, XP-Endo Finisher Retreatment (XP-Endo Finisher R, FKG Dentaire SA, La Chaux-de-Fonds, Switzerland), has been developed. This instrument, with a #30 tip size, achieves a flexible, sinuous, “snake-like’’ shape at body temperature owing to a special alloy called MaxWire (Martensite–Austenite Electropolish Flex). This feature conforms to root canal anatomy, making it more effective for removing residual filling material, especially during retreatment. During rotary motion, the tip adopts a “spoon-like’’ shape, abrading the canal walls and aiding in the removal of filling material residue. Recent micro-computed tomography (micro-CT) studies have shown that the XP-Endo Finisher R can reduce the amount of filling material remaining in the root canal; however, it has also been reported that it cannot completely remove debris from the canal, as is the case with passive ultrasonic irrigation (PUI) (Fig. 9b) (50-52).

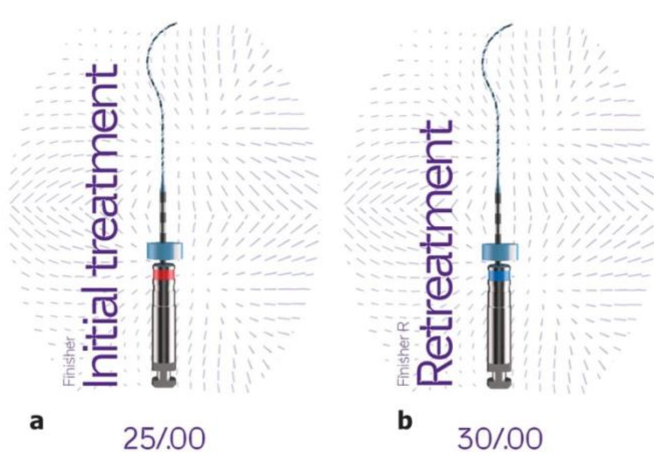

Figure 9. **(a)** XP-Endo Finisher and, **(b)** XP-Endo Finisher Retreatment (53).

In their study, Silva et al. (54), evaluated the phase transition temperatures of XP-Endo Finisher instruments and the irrigation temperatures within the root canal during rest and activation. According to the study findings, the reverse phase transition occurred at a lower temperature than that reported by the manufacturer. In addition, there was no notable variation in the temperature of the irrigating solution inside the canal when comparing the resting phase with the activation phase (54).

Silva et al. evaluated whether supplementing reciproc file use with an XP-Endo Finisher would improve the removal of bioceramic-based filling material from the canal walls. Their results demonstrated that incorporating the XP-Endo Finisher led to a significantly greater reduction of residual filling material compared to using reciprocation (55).

In a study assessing the ability of the XP-Endo Finisher R to eliminate remaining filling material from curved mesiobuccal canals of maxillary molars, its performance was compared with PUI. The results indicated that both techniques enhanced the removal of residual filling material during retreatment. However, the XP-Endo Finisher R achieved a greater degree of material removal than PUI in curved canals (52). Especially in curved and hard-to-reach canals, the ability of the XP-Endo Finisher R to conform to the canal walls and change shape can provide a significant advantage in retreatment cases by enabling more effective and comprehensive removal of the existing filling material.

3.2.4. F-file

The F-file (Engineered Endodontics, Menomonee Falls, WI, USA) is a rotary finishing instrument made from a polymer material and coated with diamond particles. It features an apical diameter equivalent to a size 20 and a 0.04 taper. This instrument was designed to enhance the removal of dentinal debris and promote better circulation of irrigants without requiring further enlargement of the prepared root canal. Studies have shown that it is effective in removing the smear layer from the entire canal system. For clinical use, the file is introduced to a position 1–2 mm short of the working length and operated with a torque-controlled electric micromotor at approximately 900 rpm, using passive insertion combined with gentle rotary axial movements, as recommended by the manufacturer (56, 57).

Ballal et al. found that the XP-Endo Finisher achieved a reduction in colony-forming units comparable to that obtained with passive ultrasonic activation during clinical root canal procedures. In contrast, the use of the F-file resulted in a higher number of colony-forming units than both the XP-Endo Finisher and ultrasonic activation; however, it still performed significantly better than conventional syringe irrigation alone. The authors emphasized that further research, particularly employing molecular diagnostic techniques, is necessary, especially for cases involving complex root canal anatomies (57).

3.2.5. Gentlefile system, Finisher GF brush

The Gentlefile system (MedicNRG, Kibbutz Afikim, Israel) is a modern root canal instrumentation system that consists of a cordless handpiece, files for root canal shaping, and a Gentlefile Finisher Brush for irrigant activation. The files in the system are based on a central braided wire with a diameter of <0.15 mm in the apical third, which is wrapped around a second wire with a diameter of <0.20 mm. A third wire with a diameter of <0.35 mm surrounds the second wire in the mid- and coronal regions. All files have a 4% fixed taper and a non-cutting passive tip. Tip diameters of 0.21, 0.23, 0.26, 0.29, and 0.34 mm do not directly conform to the standard ISO instrument sizes. The key difference between this system and traditional rotary NiTi files is that they remove dentin not by cutting, but by controlled abrasion from the surface. The files of the Gentlefile system are activated by a special micromotor operating at a speed of approximately 6500 rpm, and its automatic settings cannot be changed (58, 59).

The Gentlefile system includes a finishing brush, known as the GF Brush, which is composed of six flexible stainless-steel strands. When used with a handpiece operating at approximately 6500 rpm, these wires expand outward automatically, allowing the brush to adapt to the shape of the root canal walls (Fig. 10) (58, 59).

Figure 10. Gentlefile system, Finisher GF Brush (60).

Neelakantan et al. found the least amount of pulp residue was found in root canals shaped with the Gentlefile system and subsequently activated with the Finisher GF Brush. When root canals were prepared to a larger size (e.g., size 25), activating the irrigant with the Finisher GF Brush was found to be significantly superior to irrigation with the syringe alone in removing residual tissue (58).

Pawar et al. evaluated the ability of the Finisher Gentlefile brush, XP-Endo Finisher, and PUI to remove calcium hydroxide from root canals. Their findings indicated that the Gentlefile brush achieved significantly better cleaning outcomes than both the XP-Endo Finisher and ultrasonic irrigation. Notably, its superior performance was consistent regardless of the canal's anatomical shape or the specific intracanal medicament used, highlighting it as a particularly effective and promising option (61).

3.2.6. Easy Clean plastic file

The newly launched Easy Clean plastic file (BassiEndo, Minas Gerais, Brazil) features an innovative design aimed at enhancing the effectiveness of irrigants in root canal treatment. This 25/0.04-sized device resembles a rotary endodontic instrument and stands out with its "aircraft wing" shaped cross-section that used in both reciprocating or rotary motion to enhance endodontic cleaning and disinfection. It is manufactured from acrylonitrile butadiene styrene (ABS) plastic to provide high flexibility. Owing to its unique structure, it aims to increase the effectiveness of irrigation by creating effective fluid movement within the root canal (62, 63).

Easy Clean operates using a reciprocal motion mechanism that rotates 180° clockwise and then 90° counterclockwise. This kinematic model provides safe use by reducing the risk of the file breaking or jamming inside the canal. Studies have shown that Easy Clean allows the irrigation solution to effectively penetrate simulated lateral canals and provides superior results compared to PUI in removing the smear layer in the apical triad region (Fig. 11) (62, 63).

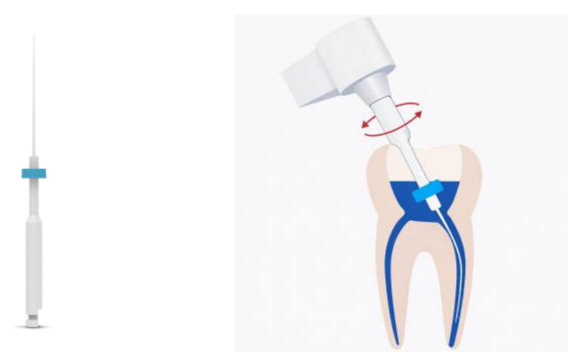

Figure 11. Easy Clean plastic file (64).

3.2.7. Easy Clean Maxx plastic file

Easy Clean Maxx (BassiEndo, Minas Gerais, Brazil) combines the efficiency of advanced technologies with practical ease of use, offering effective solutions to problems associated with ultrasonic and laser systems, according to the manufacturer's statements. This increases safety during use and significantly reduces the risk of breakage. The product is available in three different diameter options (#20, #30, and #40 mm) with a .04 taper, allowing the operator to use the device in a manner suitable for the unique anatomy of each canal. Furthermore, its design, which is 6 mm shorter than the previous model, facilitates placement, particularly in the posterior regions of the arch, increasing its usability in difficult cases. The fact that each diameter option is uniquely identified by a color (yellow, blue, and black) provides professionals with greater practicality during the procedure (Fig. 12) (64).

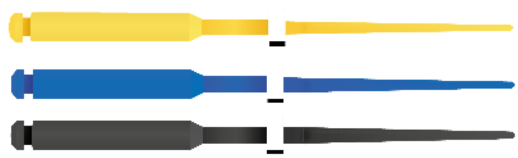

Figure 12. Easy Clean Maxx plastic file (64).

The product, offered by the manufacturer in a practical and sterile packaging concept, is prepared in a sterile blister form and delivered to users in packs of three or five. On the other hand, Easy Clean Maxx is an upgraded version of Easy Clean that retains all its advantages while offering enhanced safety, versatility, and ease of use. The manufacturer states that it is an ideal choice for professionals seeking high quality without compromising on simplicity and budget-friendly solutions in clinical applications (64).

3.3. Continuous irrigation during instrumentation with rotary instruments

3.3.1. Quantec-E irrigation system

The Quantec-E irrigation system (Sybron Endo, Orange, CA, USA) is an irrigation unit with an integrated fluid delivery mechanism. The system consists of a pump console, two separate irrigation solution reservoirs, and connection lines that provide uninterrupted irrigation during the rotary instrumentation. Continuous and active movement of the irrigant during rotary file use increases the irrigant volume, prolongs the solution contact time within the canal, and allows the irrigant to reach the deeper areas of the root canal. These features help achieve more effective root canal debridement compared to traditional syringe-needle irrigation (65).

A study has shown that the Quantec-E irrigation system is effective in improving the cleanliness of the canal wall surfaces. The results indicate that this system removes debris and smear layers, particularly in the coronal third of the canal, better than other methods (66).

3.4. Sonic Irrigation

Sonic irrigation operates at a lower frequency range (1-10 kHz) than ultrasonic irrigation. This lower frequency results in lower fluid velocity and lower shear stresses applied to the walls. However, sonic activation produces vibrations at wider amplitudes (especially in horizontal tip movements). Sonic and ultrasonic devices differ in terms of vibration (oscillation) patterns. In sonic instruments, the points where the vibration is at its minimum level are defined as nodes, whereas the points where it is at its maximum level are defined as antinodes. Sonic tips typically have a node at the device connection point and an antinode at the free tip (34).

If the free movement of these ends is restricted in any way, the horizontal oscillations cease, and the vibrations continue only in the longitudinal direction. This type of vibration pattern is particularly effective in root canal cleaning, as this mode can move with a large amplitude without experiencing a loss of performance under load (27).

The results of a recently published meta-analysis of 15 in vitro studies revealed significantly lower smear layer scores, particularly in the apical region, in root canals treated with sonic activation. In contrast, the push-out bond strength, which refers to the bond between the root canal filling material and dentin, was reported to be significantly higher in root canals treated with ultrasonic irrigation. However, no significant differences were observed between the two methods in terms of the amount of debris removed during endodontic treatment, rate of canal cleaning, or depth of irrigant penetration into the dentinal tubules (67).

While older-generation sonic agitation devices (e.g., Ripsisonic and Shapersonic, Micro-Mega, Besançon, Cedex, France) used metal files to vibrate the irrigant, the preferred sonic activation systems today operate with flexible, non-cutting polymer tips. The oscillations generated by these polymer tips, driven by sound energy, create a hydrodynamic effect called acoustic current, which aims to disrupt the smear layer and bacterial biofilms on the canal walls (68-70). Examples of modern sonic activation devices include the EndoActivator (Dentsply Sirona, Charlotte, NC, USA), EDDY system (VDW, Munich, Germany), and recently launched SmartLite Pro EndoActivator (Dentsply Sirona, Charlotte, NC, USA).

3.4.1. Rispisonic, Helisonic, Shapersonic file

Rispisonic, Shaper, and Heliosonic are traditional sonic tools that operate at sonic frequencies and have cutting ability (71). Several variables can influence the cutting performance of the sonic instruments. These include the structural differences among devices such as the Heliosonic (with grooves), Rispisonic, and Shaper (with spikes), as well as the adjustment of the handpiece's air inlet ring, which has been reported to have an optimal clearance setting. In addition, the amount of force applied by the clinician also plays an important role in their cutting efficiency (72-74).

3.4.2. Vibringe irrigation device

Vibringe (Cavex Holland BV, Haarlem, Netherlands) is a device that combines manual solution delivery with sonic activation. It is a wireless handpiece designed to be attached to a specially designed, single-use syringe compatible with any irrigation needle. It delivers irrigation fluid directly into the root canal through a standard needle in a continuous, vibrating manner. It works by combining sonic flow technology with acoustic flow (Fig. 13) (75).

Figure 13. Vibringe irrigation device (76).

3.4.3. EndoActivator system

The EndoActivator system (Dentsply Sirona, Charlotte, NC, USA) is a sonic device designed to enhance irrigant activation by promoting vigorous fluid agitation inside the root canal. Studies have demonstrated that it improves the effectiveness of irrigation compared to conventional syringe delivery. The system includes a cordless handpiece and three single-use flexible polymer tips available in sizes 20/0.02, 25/0.04, and 30/0.06, which are color-coded yellow, red, and blue, respectively. Notably, these polymer tips are gentle on dentin and do not produce canal wall abrasion (Fig. 14) (77).

Figure 14. EndoActivator system (78).

The combination of the tip's horizontal movement and short vertical movements creates a powerful hydrodynamic effect within the root canal, working in synergy. This action enables the irrigating solution to reach areas of the canal that are otherwise difficult to access, improving fluid circulation and movement, which in turn enhances the overall cleaning effect. However, one drawback of the polymer tips used with the EndoActivator is their radiolucency. Although the tips are intended for single use and are generally resistant to breakage, if a fragment separates within the canal, it may be challenging to locate it on a radiograph (27). This situation becomes even more important when working in narrow and curved root canals. This is because the tips are more susceptible to mechanical stress in such anatomical areas, which can increase the risk of fracture. If a fragment that is not visible on the radiograph remains undetected in the canal, it can lead to continued infection, symptom recurrence, and treatment failure.

3.4.4. SmartLite Pro EndoActivator system

Similar to the first-generation EndoActivator, the second-generation SmartLite Pro EndoActivator system is available with three different sizes of polymer tips (small 22 mm: 15 gauge/0.02 taper; medium 22 mm: 25 gauge/0.04 taper; long medium 28 mm: 25 gauge/0.04 taper). The long medium tip was specifically developed for effective access in teeth with longer root lengths. However, unlike the first-generation tip, the second-generation tip feature a variable cross-section design. They operate with a higher frequency elliptical motion, allowing for more effective movement of the irrigant within the canal. Unlike the circular tip of the first generation, the second-generation tips have a paddle-like and parallelogram-shaped cross-section. The SmartLite Pro EndoActivator features a removable treatment head that can be replaced with a light-curing head, if necessary. The device operates at two different speed settings (3,000 rpm and 18,000 rpm), providing elliptical movement and increased energy transfer during irrigant activation (Fig. 15) (79).

Zeng et al. reported that, based on the constraints of their in vitro investigation, the two sonic irrigation activation systems, EndoActivator and SmartLite Pro EndoActivator, did not show a statistically significant difference in their ability to reduce bacterial load within the root canal (79).

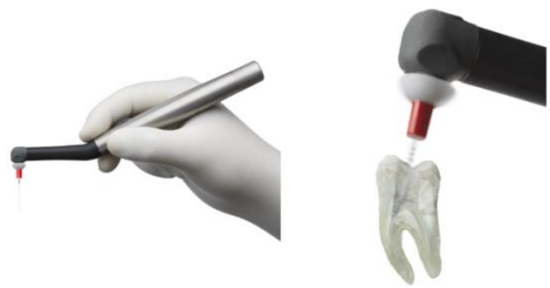

Figure 15. SmartLite Pro EndoActivator system (78).

In a study by Bolla et al., the effectiveness of sonic activation in root canal decontamination was assessed using an endocator adenosine triphosphate (ATP) measurement system. Their results showed that the four experimental groups demonstrated reductions in initial ATP levels of 99.8%, 99.9%, and up to 100%. Notably, the combination of 1% NaOCl irrigation with the SmartLite Pro EndoActivator achieved complete elimination of detectable ATP after just two activation cycles, and this result was maintained consistently through the ninth cycle, without any rebound in ATP or colony-forming unit (CFU) levels. These findings indicate that when the initial bacterial load is low, complete microbial reduction within the canal may be achieved rapidly and with relative ease (80). The varying results obtained in studies conducted with the SmartLite Pro EndoActivator regarding bacterial elimination necessitate a reassessment of the effectiveness of irrigation protocols, not only for this device but also for other activation systems. Therefore, further comparative studies with different activation devices are essential to determine the most effective irrigation strategies for microbial elimination.

Myint et al. demonstrated that the SmartLite Pro EndoActivator was superior to both the EndoActivator and syringe irrigation in terms of cleaning effectiveness without the need for multiple vertical strokes. However, they emphasized that clinicians should avoid excessive vertical strokes because of the risk of irrigant extrusion beyond the root apex (81).

3.4.5. EDDY sonic irrigation system

The EDDY (VDW, Munich, Germany) was developed as a sonic energy irrigation activation system manufactured from a flexible polyamide material measuring 25.04 mm. The manufacturer states that this system enables effective cleaning of complex root canal anatomies without the limitations of ultrasonic devices. The EDDY is activated using an air-powered handpiece (Air Scaler) at a frequency of approximately 5000–6000 Hz. During this activation, passive ultrasonic irrigation generates a three-dimensional oscillation that generates cavitation and acoustic current, two important physical effects that increase cleaning success. It is also emphasized that the EDDY is a non-cutting, sterile, and single-use instrument (Fig. 16) (82).

In studies comparing Endoactivator and EDDY in relation to the reduction of intracanal bacteria, Zeng et al. demonstrated that, within the limitations of their current study, there was no difference in antibacterial efficacy between the two sonic-assisted root canal irrigation activation systems tested using 2% NaOCl (84). Swimberghe et al., in their study using a simulated canal isthmus model examining the removal of a biofilm-mimicking hydrogel, reported that EDDY provided a higher level of hydrogel removal and demonstrated better performance compared to EndoActivator (85). In another study by Swimberghe et al., EDDY provided a higher level of hydrogel removal than EndoActivator in the removal of a biofilm-mimicking hydrogel (BMH) in simulated curved root canals (86). Differences were observed in the results obtained in the studies mentioned above. These inconsistencies may largely be due to differences in the irrigation solutions used, experimental design, and sample types. Particularly in sloped and isthmus channels, the EDDY system appears to yield more effective results in terms of biofilm removal. However, more controlled and standardized studies are needed to strengthen the evidence in this area and enable a clearer clinical evaluation of the findings.

Figure 16. EDDY sonic irrigation system (83).

In a meta-analysis comparing the cleaning efficacy of EDDY and ultrasonic-activated irrigation in root canals, qualitative and quantitative evaluations of the included studies indicated that, based on the limited available evidence, EDDY was at least as effective as PUI ex vivo in removing the smear layer, debris, soft tissue debris, and bacteria. Given the potential for damage to the canal walls caused by the metal tips used in ultrasonic systems, EDDY may be a suitable alternative to PUI for activating irrigation solutions. However, due to discrepancies between in vitro studies and actual clinical conditions, it was emphasized that further randomized clinical trials are needed to assess the generalizability of these results to clinical practice (87).

Donnermeyer et al. found no statistically significant difference between EDDY and ultrasonic irrigation in removing calcium hydroxide from root canals (88). The break-resistant flexible polyamide tips of the EDDY can generate acoustic currents by creating spiral vortices along the tip. Although the EndoActivator uses flexible polymer tips, they are not as effective as EDDY's polyamide tips. EDDY's superior performance of EDDY in the removal of calcium hydroxide can be attributed to the higher oscillation frequency of the system compared that with of other sonic activation methods. The reason EDDY sonic activation is more effective in the apical triad region may be its elastic tips, which can provide an advantage over the rigid metal tips typically used in PUI applications (82).

Salas et al. evaluated the penetration of 2% chlorhexidine (CHX) into dentinal tubules using the CSI, EDDY, and PUI techniques. The three tested irrigation methods showed that the depth and area of the penetration of CHX into the cervical and mid-level dentinal tubules were similar. Statistically significant differences were found only in the apical region, where the mean for the PUI group was higher than that for the EDDY group (89). In another study, EDDY, XPF, PUI, and CSI were compared in the cleaning of modified triple antibiotic paste (mTAP) from artificially created grooves in root canals. In terms of mTAP removal, the EDDY group yielded better results than the CSI, PUI, and XPF groups (90). These results indicate that irrigation effectiveness may vary depending on the solution used, regional characteristics of the canal, the targeted clinical goal. The EDDY system may be more effective in removing medication and debris adhering to the canal walls, whereas the PUI method may offer advantages, particularly in the apical region, by allowing the irrigation solution to penetrate deeper into the dentinal tubules.

3.5. Passive Ultrasonic Irrigation (PUI)

Passive ultrasonic irrigation (PUI) was first described by Weller et al. in 1980. Although the term "passive" is used, the process is actually active; this term was chosen to emphasize the non-cutting properties of the ultrasonically activated file when the method was first introduced. PUI is based on the principle of ultrasonic waves transferring acoustic energy to the irrigating solution via a vibrating file or smooth wire. This transferred energy can cause acoustic currents and cavitation effects within the irrigant (91). Acoustic flow is defined as the rapid vortex-like circulation of irrigation fluid around a vibrating file. Cavitation, on the other hand, is a phenomenon that occurs when vapor bubbles form within the fluid, or when existing bubbles expand, contract, or change shape (92). Temporary cavitation occurs only when the file vibrates freely within the canal or lightly contacts the walls. When the canal is pre-shaped, the file or wire can move more freely, allowing the irrigant to reach the apical regions of the root canal more easily, thus increasing cleaning efficiency (92, 93).

In PUI, acoustic energy is transmitted from the ultrasonic tip to the irrigant within the root canal, typically at operating frequencies between 25 and 45 kHz. This activation promotes the elimination of intracanal medicaments by increasing the temperature of the irrigant, inducing acoustic microstreaming and microbubble activity, and generating cavitation effects (94), and provides more effective cleaning than the traditional needle technique (91). However, despite this method, curved channels (95), oval channels (96), and remnants of medication are still found in the canals of the isthmus regions located in the roots of molars and premolars (94).

Conversely, PUI generates acoustic waves that lead to the formation of cavitation bubbles in the irrigant. When these bubbles collapse, the released energy is directed toward the canal walls, helping to dislodge debris and remove the remaining medicament from the root canal system (97, 98). However, some studies have reported that ultrasonic tips cannot move freely, may adhere to walls and block acoustic flow and cavitation, and that this situation can lead to insufficient debridement, protrusion formation, and uncontrolled cutting in oval channels (99).

A review examining sonic and ultrasonic activation of endodontic sealer to improve root canal filling quality provides evidence that these two methods can increase sealer penetration into the dentinal tubules. However, the effect of these activation techniques on sealer-to-dentin bond strength remains unclear, and uncertainties persist in this area (100).

Elmaasaravi et al. evaluated the effects of different endodontic treatment protocols on tooth survival. A comprehensive treatment protocol (Protocol 3), which included the use of an apex locator, reciproc system, ultrasonic irrigation, and ethylenediaminetetraacetic acid (EDTA) application, showed superior results in terms of the tooth survival time in the mouth after root canal treatment and its survival in the mouth without requiring additional intervention (extraction, retreatment, or surgical retreatment). Compared to other protocols, this protocol reduced the need for additional intervention by approximately 30% to 40% (101).

During PUI application, the irrigation process can be performed using two different methods: continuous activation or intermittent application.

Continuous Ultrasonic Irrigation (CUI) is an irrigation method that promotes physical effects, such as micro-acoustic currents and cavitation, enabling the irrigant to be delivered into the canal in a continuous flow. In this system, the irrigation solution is delivered into the canal via a needle directly connected to the ultrasonic unit, and the solution is activated as it passes through the needle tip. This approach eliminates the need to place the needle up to the WL, as effective irrigation can be safely achieved in more coronal regions (102).

One of the fundamental effects expected from ultrasonic-activated irrigation methods, namely the formation of acoustic microcurrents, is critically dependent on the canal being completely filled with the irrigant. In this context, the regular replacement of the irrigant ensures the continuity of effective irrigation. However, the intermittent ultrasonic irrigation method is applied to a fixed irrigant volume, and this volume is depleted over time as the irrigant is transported from the ultrasonic tip in the coronal direction, thus potentially disrupting acoustic microcurrent formation (102).

PUI has been used in various protocols. In some studies, intermittent activation in three cycles of 20 s each was preferred (103, 104). On the other hand, it can also be used in a continuous activation mode for 60 s in a single cycle (105, 106). Another recommended protocol is to perform ultrasonic activation continuously for 3 min (107).

Some researchers have reported that the inclusion of EDTA in PUI protocols increases the debris removal efficiency (108, 109). However, some studies have not observed a similar effect and have found no significant difference between the use and non-use of EDTA. Another study found that EDTA/PUI removed significantly more debris in the cervical third compared to the use of EDTA alone (108).

In a study by Plazza et al., a 20-second PUI protocol (NaOCl-EDTA-NaOCl) in three cycles, a 60 s protocol in two cycles (EDTA-NaOCl), or a 60 s protocol in a single cycle (NaOCl) was more effective in removing debris and exposing dentin tubules (110).

Ultrasonic tips can be manufactured from various materials, such as stainless steel, zirconium nitride, nickel-titanium, or polymer, and can have different shapes, angles, and surface properties. These tips can operate at different frequency ranges, depending on the power level (111).

Metal tips with higher hardness and density create higher amplitude and energy density during vibration, whereas polymer-based tips demonstrate greater flexibility and allow safer irrigant activation in complex root canal anatomies (112). Furthermore, the length, taper, and overall geometric design of the tips determine the energy delivery efficiency and oscillation characteristics. Therefore, tips with shorter and more pronounced tapers are reported to direct energy more intensely to the apex region (112, 113).

When ultrasonic tips are applied to the root canal, vibration frequencies may be affected by different root anatomies, which can impact the cleaning and disinfection of root canals (114-116), agitation of irrigation solutions (114), and removal of canal-based medications (94, 116). Notably, this can compromise the clinical outcomes and quality of endodontic treatment. Therefore, metal tips may be inadequate for accommodating complex anatomies, particularly in canals with significant curvatures. In contrast, polymer tips offer significant advantages in curved, oval, or isthmus-like canal morphologies; they readily adapt to intracanal irregularities and effectively support both irrigant movement and debris removal throughout the working length (117).

Endosonic Blue (Maruchi, Wonju, South Korea) is a PUI system and features Ni-Ti files manufactured using R-Phase technology (118). This manufacturing technology provides excellent flexibility to the files and enhances their resistance to cyclic fatigue. In the Endosonic Blue system, the Ni–Ti file used has a size of 15/0.2 and operates with sonic oscillation at approximately 30 kHz (119). In the study conducted by Choi et al., Endosonic Blue demonstrated higher antibacterial efficacy and biofilm removal success compared to the Irrisafe PUI with a stainless steel tip; this is likely due to its metallurgical properties and file design (Fig. 17) (120).

Figure 17. Endosonic Blue (121).

Ultra X (Eighteeth, Changzhou City, China) is a wireless ultrasonic device featuring three specially designed tips for activating irrigation solutions. These tips (X Silver, X Gold, and X Blue) have been specifically developed for irrigant activation. The tips are available in two different lengths (18 mm for X Gold and X Blue, 21 mm for X Silver) and two different sizes (20/.02 or 25/.02). According to the manufacturer, these tips have a smooth surface coating, and the X Blue and X Silver tips provide an additional flexibility. A study suggests that the titanium-aluminum composition and smoother surface of Ultra X Silver likely contribute to its greater flexibility, making it ideal for angled canals. In contrast, Ultra X Gold's stainless steel composition may provide higher durability, but this may come at the expense of flexibility (Fig. 18) (122).

Figure 18. Ultra X (123).

EndoSonic PS (SelectD, Seoul, Korea) is a recently introduced ultrasonic-assisted irrigation activation system made of autoclavable flexible polymer material with tip sizes ranging from 20/0.03 to 25/0.03. The manufacturer states that this system is designed for use in both straight and curved root canals and allows for the safe removal of debris and smear layer. Furthermore, in the event of a fracture, the broken fragment can be easily removed from the canal using irrigation. A comparative study evaluated the smear and debris removal effectiveness of the EndoSonic PS, EDDY, and Irrisafe (metal-tipped PUI) systems. The results indicated that EndoSonic PS performed successfully in the coronal and mid-canal regions and was similar to the other two techniques in terms of debris removal in the apical region. However, EndoSonic PS was found to be less effective than the other two activation protocols in removing the smear layer in the apical region (124).

Güven et al. evaluated several irrigant activation methods for their ability to remove calcium hydroxide. Their results indicated that EDDY and Ultra X achieved superior removal of calcium hydroxide from artificial grooves on root canal walls compared to the Endosonic Blue and EndoActivator systems (125).

When these findings are evaluated overall, it is seen that the effectiveness of ultrasonic activation systems depends not only on the technology used but also on the clinical decision-making process. While each system offers advantages in specific anatomical situations, there is no single option that can be universally described as the “best” approach. For example, metal tips with high rigidity are effective in straight and wide canals, whereas flexible polymer or NiTi tips can provide a more suitable performance in terms of both safety and irrigant activation in curved or oval canals. Therefore, the clinician’s accurate assessment of the canal anatomy and adaptation of the activation protocol to the canal geometry directly affects the success of the treatment. Furthermore, studies have shown that different systems perform at different levels in specific areas, suggesting that irrigation should not be limited to a single technique and that combined approaches or region-specific activation strategies may be more effective when necessary. In conclusion, when irrigation activation is approached as “selecting the appropriate tools and methods for the situation” rather than “device selection,” it is clear that both the level of disinfection and clinical success rates will increase.

3.6. Generate sequential pressure systems

Due to the challenges of safely and effectively delivering irrigant to the most apical regions of the root canal system and the risk of unintentional irrigant extrusion beyond the apical foramen, the apical negative pressure (ANP) irrigation technique has been developed in endodontics. Numerous studies have shown that this technique provides more effective cleaning and disinfection than positive pressure (PP) irrigation and significantly reduces apical extrusion. This method is thought to eliminate the vapor lock that forms in the apical region, allowing for more efficient irrigant flow, thus making apical root canal debridement more effective (126).

3.6.1. EndoVac system

The EndoVac system (Discus Dental, Smart Endodontics, Culver City, CA, USA) is designed to irrigate the root canal using ANP, allowing the irrigants to be safely drawn down to the apex and into areas that are otherwise difficult to access. The system is composed of three primary elements: a master delivery tip for introducing the irrigant, a plastic macrocannula with a 0.55 mm diameter and 0.02 taper for removing coarse debris from the coronal and middle thirds, and a stainless-steel microcannula with a 0.32 mm diameter and a closed end. When the canal has been enlarged to at least a size 35 preparation, the microcannula can be advanced to the full working length for effective apical cleaning (126).

To examine the antimicrobial efficacy of the EndoVac system, Cohenca et al. compared ANP irrigation with conventional irrigation and a triantibiotic intracanal dressing for root canal disinfection in canines. ANP irrigation with EndoVac was found to be a promising disinfection method for immature teeth with apical periodontitis, as this technique provided bacterial reduction as effective as conventional positive-pressure irrigation supplemented with a triple antibiotic paste. In conclusion, the study demonstrates that adequate disinfection is possible with safe and effective irrigation systems such as EndoVac, and that intracanal antibiotic use may not be necessary in all cases (127).

Mancini et al. compared the effects of different irrigation systems (EndoActivator, EndoVac, and PUI) on the removal of the smear layer and canal cleaning. The results showed that the EndoVac system removed statistically significantly more smear layer than all other groups at 1, 3, 5, and 8 mm from the apex. No significant difference was found between PUI and EndoVac at 5 and 8 mm from the apex; however, both systems provided significantly better cleaning than the control groups (105).

Karataş et al. compared apical debris extrusion using different irrigation techniques. According to the study results, the SAF and EndoVac groups caused less extrusion than the PUI group (128).

In conclusion, studies in the literature show that the EndoVac system is both an effective and safe option for root canal disinfection. The ANP principle, it ensures that the irrigation solution reaches the apex region in a controlled manner, thereby increasing bacterial elimination and reducing the outward transport of debris from the apex. Furthermore, its disinfection success rate, which is similar to that of antibiotic-impregnated dressings, suggests that it may reduce the need to place medication inside the canal in some clinical situations. The positive results obtained in removing the smear layer and protecting apical tissues also demonstrate that the EndoVac system offers a significant advantage in endodontic treatments, where the safe and effective cleaning of the apical region is targeted.

3.6.2. Total Vac system

The TotalVac system (Brasseler, Savannah, GA, USA) was developed to mimic the ANP principle of EndoVac. The system consists of a TotalVac tube with a suction head designed similar to the EndoVac main delivery tip, which delivers a large-volume irrigant to the pulp chamber. It also includes a plastic suction tip similar to a macrocannula to aid in the removal of coarse tissue debris. A 30-gauge side-hole needle is used to create the microcannula effect of the EndoVac. Brasseler, the manufacturer, promotes TotalVac as an economical and versatile option that combines the advantages of positive and negative pressure irrigation during root canal treatment (Fig. 19) (129).

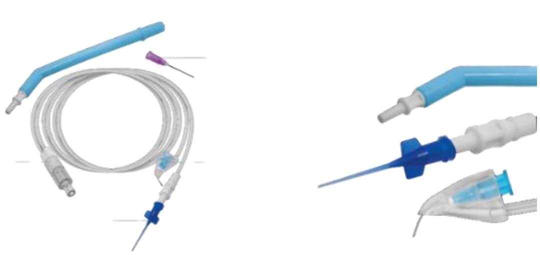

Figure 19. Total Vac (130).

3.6.3. PulpSucker system

The Pulp Sucker (PlanB Dental, Goleta, CA, USA) is a device developed to facilitate the removal of pulp tissue and debris from the root canal. This system creates negative pressure in the pulp chamber, allowing automatic, continuous, and multichannel irrigation throughout the root canal system. As a result, irrigation solutions are passively and completely controlled drawn out from the tips of the cannulas, and fresh irrigation solutions are delivered to the canal. A kit containing the equipment to be used in the final irrigation phase is available for each tooth type. This kit includes equipment such as the SmearOff injector (17% EDTA + CHX), placement device, placement tool, VacuSeal, and Clor-XTRA Plus (enhanced 8.0% NaOCl) (Fig. 20) (131).

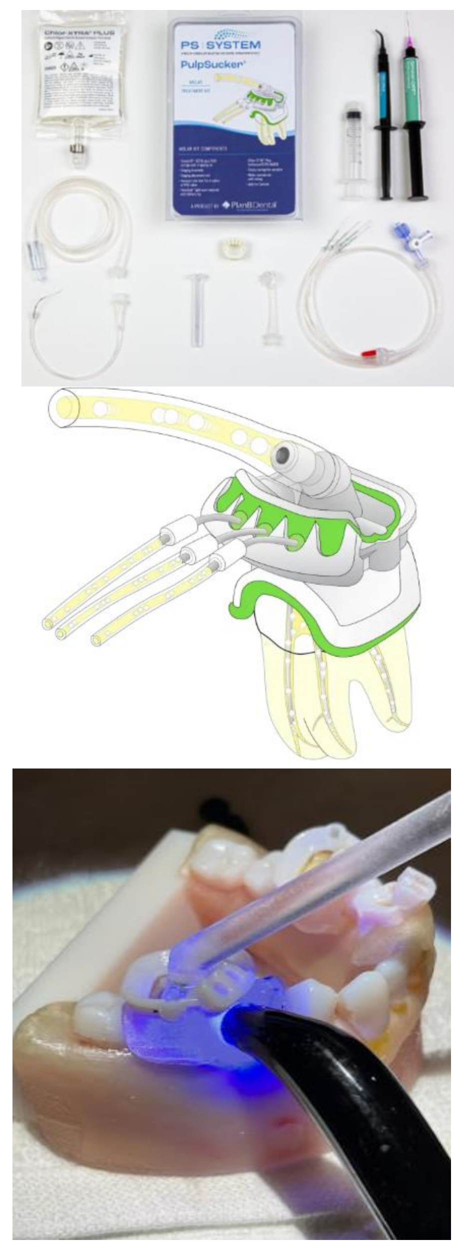

Figure 20. PulpSucker (132).

3.6.4. iVac system

The iVac system (Pac-Dent, Brea, CA, USA) combines three different activation techniques (131):

1. Piezoelectric ultrasonic activation: According to the manufacturer, it can generate vibrations in the approximate 30 kHz frequency range, creating temporary cavitation and microstreaming effects.
2. Negative pressure: This allows irrigants to flow from the pulp chamber toward the apical tip, but no extrusion occurs outside the foramen.
3. Simultaneous irrigation: This technique ensures that the irrigant volume is continuously replenished in large quantities, thereby maintaining the effectiveness of the irrigants.

The flexible polymer tip used for activation and aspiration with ANP in the iVac system operates at lower frequencies because of its material properties. This is because polyethylene has acoustic absorption properties, its elastic modulus ranges from 1 to 5 GPa, and its density ranges from 0.9 to 2 g/cm^3 (133).

Additionally, this material has a high damping capacity due to its vibration absorption and reduction properties; therefore, it operates with lower vibration intensity and dissipates some ultrasonic energy by converting it into heat. This feature makes it suitable for more sensitive processes (112, 113). In addition, polymers may exhibit a range of structural arrangements, from semi-crystalline to fully amorphous forms. The polymer chains are connected by relatively weak intermolecular interactions, including van der Waals forces and hydrogen bonding. This type of bonding network contributes to the characteristic flexibility of the material (134, 135).

Therefore, metal tips may be limited in their ability to adapt to complex root canal anatomy, particularly those with significant curvatures. In contrast, polymer tips offer a distinct advantage in curved, oval, or isthmus-shaped canals. They adapt easily to the internal structure of the canal, helping to effectively remove both debris and irrigant throughout the working length (117). Therefore, the use of flexible polymer tips, such as iVac, can be considered an effective alternative in clinical situations requiring safety and flexibility while maintaining canal cleaning and disinfection efficacy (136).

In a study evaluating the performance and frequency characteristics of polymer, steel, and titanium ultrasonic tips for intraroot medicament removal, the frequencies generated by these tips were examined using acoustic wave analysis. Furthermore, the effectiveness of PUI with the iVac system in removing calcium hydroxide-based intraroot medicament was compared with conventional irrigation techniques and analyzed using micro-CT. The micro-CT results revealed that the iVac system demonstrated the highest efficacy in removing root canal medicament debris compared to both PUI and conventional irrigation (Fig. 21) (136).

Figure 21. iVac system (132).

Arıcan et al. compared the effectiveness of PUI, EDDY, iVac, Pulp Sucker, and CSI techniques in removing $Ca(OH)_2$ from simulated internal resorption defects. The study findings showed that PUI and EDDY removed significantly more $Ca(OH)_2$ than Pulp Sucker, CSI, and iVac. Furthermore, no statistically significant difference was found between the Pulp Sucker and CSI (137). Atav et al. compared the effectiveness of the control group, conventional irrigation, PUI, laser-activated irrigation (LAI) with distilled water, PulpSucker, and iVac techniques in removing the smear layer in root canals. The study determined that iVac provided the most successful results in removing the smear layer, particularly in the apical third. The researchers stated that the superior cleaning efficiency of iVac compared to other methods may be due to the combined action of different mechanisms, which enhances the fluid dynamics of the system and, consequently, allows for more effective chemical disinfection (131). When both studies are evaluated together, it is understood that different techniques can demonstrate varying levels of success in different clinical scenarios. Therefore, in order to speak of a definite superiority among irrigation systems, there is a need for larger-scale studies with high standardization that reflect real clinical conditions. Furthermore, investigating whether the combination or sequential use of these techniques contributes to efficacy would be valuable for future studies.

3.6.5. Endo Irrigator Plus (K Dent dental system)

The Endo Irrigator Plus (Dombivli, Mumbai, Maharashtra, India) is an irrigation system developed by Dr. Mandar Pimprikar and operates on the principle of activated continuous warm irrigation and drainage system (ACWIS). The device uses a pressure-assisted mechanism that creates both positive and negative pressure within the root canal. Controlled by a foot pedal, the system features a built-in heating unit that warms the NaOCl solution to approximately 50°C and an integrated suction module that ensures safe irrigant removal. Continuous heating of the irrigant allows for better NaOCl penetration into the lateral and accessory canals, while the powerful vacuum prevents the irrigant from being carried into the periapical tissues. Gadaalay et al. reported that the Endo Irrigator Plus's cleaning efficacy was superior to similar irrigation systems. Another study demonstrated that the Endo Irrigator Plus significantly reduced the amount of residual material transported into the periapical region. Therefore, it is known that this system provides effective disinfection and cleaning and does so in a relatively safe environment (138, 139).

3.7. Multisonic activation: GentleWave® system

A new device known as the multisonic ultracleaning system (GentleWave®, Sonendo, Laguna Hills, CA, USA) has recently been developed for cleaning root canals. The system operates via a handpiece placed on the occlusal surface of a previously accessed tooth and is activated from a computer console. Additionally, the system incorporates a technology called multi-sonic ultrasonic cleaning, which relies on energy generated by various sound wave frequencies across a wide range. This technology is accompanied by irrigant solutions such as sodium hypochlorite (3%), pure water, and EDTA; 8%. The machine alters the flow of the irrigation fluid, allowing it to interact with the fluid remaining in the pulp chamber; this interaction creates a shear force that generates microbubbles via hydrodynamic cavitation (140).

In the GentleWave® system irrigation protocol, the irrigant is delivered at a rate of approximately 50 mL per minute over an 8-minute activation period, resulting in a total volume of approximately 400 mL being circulated through the root canal system under multisonic activation (141).

GentleWave® system has an integrated suction feature that removes fluids and debris owing to the negative pressure created within the root canal system, ensuring cleanliness at the crown-apex level (142, 143). Additionally, according to the manufacturer, the canals can be treated with minimal instrumentation and do not need to be enlarged beyond the ISO 15 size; thus, the tooth structure is preserved (143).

Recently, the GentleWave® G4 System, supported by the ProControl™ software update, has been introduced, enabling precise adjustment of NaOCl concentration up to 5% in cases involving vital tissue and allowing optimized debridement in anatomically complex root canal systems. In a study conducted by Gündoğar et al., existing conventional and advanced irrigation activation techniques were compared in necrotic oval root canals following minimally invasive instrumentation. According to the histological analysis results, the GentleWave system used with the updated software demonstrated a statistically significantly higher debridement efficacy in the removal of residual necrotic tissue and debris in the apical region compared with passive ultrasonic activation, laser-activated irrigation methods (Er:YAG and Er,Cr:YSGG), and CSI (144).

Cleanflow is a next-generation GentleWave® system handpiece that can be used on all tooth types, unlike handpieces designed for anterior/premolar or molar teeth. In traditional designs, the soundbar of the molar handpiece is positioned outside the handpiece to induce hydrodynamic cavitation in the pulp chamber and provide multisonic activation throughout the root canal system. With CleanFlow, this design has been revisited, and the soundbar is integrated into the body of the handpiece. This innovation aims to simplify system use while maintaining efficiency (141).

A study comparing the efficacy of GentleWave® system CleanFlow in removing *Enterococcus faecalis* biofilm in uninstrumented and minimally instrumented root canal systems found that both irrigation protocols resulted in a significant reduction in *E. faecalis* cultures compared to the positive control group. However, no statistically significant difference was observed between the tested protocols (141).

Crozeta et al. evaluated the effectiveness of the PUI and GentleWave® systems as auxiliary techniques for removing residual filling material from oval-shaped root canals. PUI demonstrated better performance by removing 18% of the residual filling material, whereas the GentleWave® system was able to remove approximately 10% (145).

In a study evaluating postoperative pain in patients treated with the GentleWave® system, patients in the control group received endodontic treatment with conventional side-hole needle irrigation and ultrasonic activation, whereas the second group received treatment with the GentleWave® system. Postoperative pain was reported at least once in 72.2% of patients treated with standard treatment compared with 83.3% in the GentleWave® group. However, no statistically significant difference was found in the severity and frequency of postoperative pain in either group (146).

Compared to traditional methods, GentleWave® system has demonstrated significantly higher cleaning capacity and greater debris removal success in the mesiobuccal and mesiolingual canals of lower molars and mesiobuccal canals of upper molars (142).

Recently, a review was published explaining the results of GentleWave® system in endodontic treatment. Overall, the results showed that GentleWave® system reduced bacterial DNA, accelerated the dissolution of organic matter, and supported deeper penetration of sodium hypochlorite into the dentinal tubules (147).

Based on these varying results, it is evident that there is no consensus in the literature regarding the effectiveness of the GentleWave® system for endodontic treatment. While some studies suggest that the system may offer advantages in terms of cleaning capacity and irrigation effectiveness, other studies have shown that it does not offer clear superiority over traditional methods in terms of clinical outcomes. Another comprehensive review noted that the existing evidence for GentleWave® system is largely based on in vitro studies and for clinical studies, and therefore, knowledge regarding the use of this technology is still quite limited. It was emphasized that caution should be exercised in clinically recommending GentleWave® system, as evidence of its superiority has been obtained solely from in vitro studies. Furthermore, considering its high cost compared to other systems on the market, it was stated that the lack of an assessment of its cost-effectiveness is a significant shortcoming (148).

Therefore, in order to make a definitive recommendation regarding the routine use of GentleWave® system, there is a need for clinical studies that evaluate more comprehensive and long-term results are needed.

3.8. Photoactive disinfection (PAD)

Photoactive disinfection (PAD) is a novel approach based on the principle of applying a photosensitizer (a non-toxic dye) to the dental canal, which then interacts with low-intensity light to release reactive oxygen species. The dye binds to the cells and, when exposed to a specific light source, releases free oxygen, damaging the cell membrane. As Komerik et al. pointed out, this dye has a lower affinity for human cells (149).

Examples of photosensitizers applied to the root canal include methylene blue, tolonium chloride, polyethyleneimine and chlorine (e6), Phenothiazinium, Chitosan, Rose Bengal, Malachite green, and indocyanine green. There is significant evidence for indocyanine green, toluene chloride, and methylene blue; however, evidence for rose bengal, malachite green, and indocyanine green is quite limited. Although the role of tholonyum chloride in photoactive disinfection has been established, further studies are needed in the future to reach definitive conclusions regarding the value of using these other agents alone or in combination (150).

PAD is an antimicrobial method effective not only against bacteria but also against fungi, viruses, and other microorganisms. During application, a photosensitizer dye is placed in the root canal and left in place for approximately 60 s, followed by 30 s of light activation. Bunsor and Schlafer have shown this method to be effective in eliminating microorganisms. However, PAD should not be considered a standalone method to replace irrigation, but rather a complementary technique to support irrigation protocols (151, 152).

PAD has been shown to decrease bacterial levels in root canal therapy in both laboratory and clinical studies. Previous systematic reviews have indicated that this method is effective against *E. faecalis* when applied within the root canal system (153, 154).

In acute exacerbations occurring during endodontic treatment, strictly anaerobic microorganisms such as *Porphyromonas endodontalis* are often among the primary pathogens. Similar to other gram-negative bacteria in the root canal system (e.g., *Prevotella intermedia*), such microorganisms are highly sensitive to singlet oxygen and are therefore easily inactivated. This feature supports the addition of PAD as an effective complementary approach to existing chemomechanical root canal preparation methods (155, 156).

Photoactivation using methylene blue may be valuable in cases of retreatment performed with traditional (anterograde) endodontics or in surgical endodontic applications. This method, when combined with traditional treatment, can further reduce the bacterial load and improve the prognosis of the case after treatment (157). A methylene blue concentration between 0.001% and 0.1% appears to be the most effective range for singlet oxygen production (158). An illumination time of only 30 s may not provide adequate antimicrobial activity, whereas extending the irradiation of the photosensitizer to 60 s or 120 s has been shown to markedly enhance its antibacterial effectiveness (159).

In general, one of the most useful applications of PAD may be to eliminate persistent endodontic infections in cases where traditional methods have failed (160).

3.9. Laser activation

Root canal disinfection can be achieved using various methods, one of which is the use of laser light. Diode and Nd:YAG lasers produce thermal energy to destroy bacteria; however, this heat can potentially cause thermal damage to surrounding tissues, especially if pigment is present in the root canal (161). However, while these lasers cannot remove the smear layer, near-infrared lasers can provide both debris removal and bacterial elimination (Fig. 22) (161). Another issue in diode and Nd:YAG laser applications is that the fiber tip must reach the end of the channel. This depends on the shape of the channel and can be limiting in angled channels, as it carries the risk of damaging the channel's tip (162).

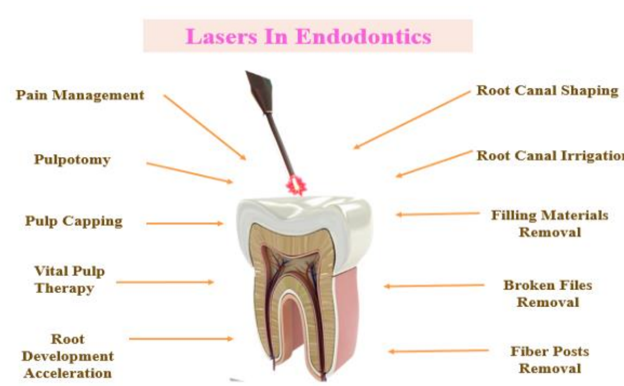

Figure 22. Current and advanced application areas of lasers in endodontic treatment.

Laser-assisted irrigation (LAI) was first introduced years ago as an adjunct technique to root canal irrigation (163). In this technique, fiber tips are used to create microcavitation bubbles in the irrigation solution. The volumetric expansion and contraction of the bubbles causes the fluid to move at high speed, displacing the biofilm and debris in the root canal along its longitudinal axis. The resulting continuous and powerful flow allows debris attached to the canal walls to be dissolved, dislodged, and then effectively removed (164).

Photon-induced photoacoustic streaming (PIPS), an emerging LAI technique, was introduced for clinical use in 2012. Compared to traditional LAI methods, PIPS offers features such as low energy (10 or 20 mJ) and a short pulse duration (50 µs) (164). Moreover, by positioning the working tip in the coronal region of the canal, this technique helps avoid excessive heat transfer to the canal walls and surrounding periapical tissues, thereby minimizing the risk of thermal damage (165).

A study evaluating the antibacterial effect of the PIPS technique in root canals prepared with different diameters and tapers observed that increasing the canal width increased the bactericidal effect of PIPS when applied at the same taper value. However, it was reported that increasing the taper in #25 canals did not significantly improve the antimicrobial success of PIPS. PIPS exhibited a stronger antibacterial effect in canals with narrower diameters and lower tapers. Furthermore, PIPS effectively removes the smear layer in the coronal region of the root canal and facilitates the opening of dentinal tubules (165).

The Shock Wave-Enhanced Emission Photoacoustic Streaming (SWEEPS) technique was developed to enhance the debridement effectiveness of the PIPS method. While SWEEPS is similar in principle to PIPS, its mechanism of action is different; in this method, sequential (double-pulsed) laser energy is delivered to the irrigation fluid. The pressure waves generated by SWEEPS are stronger than the single-pulsed Er:YAG laser application used in the standard PIPS protocol, thus significantly enhancing the photoacoustic streaming effect within the fluid (166). As the initial cavitation bubble starts to collapse, a second laser pulse was delivered into the irrigant, creating a new cavitation bubble. This second bubble enhances and accelerates the collapse of the first bubble, resulting in a forceful implosion that produces a shock wave. In addition, secondary cavitation bubbles that form and collapse close to the root canal walls release further shock waves, helping to dislodge and remove debris that is adhered to the canal surfaces (167).

In a study using micro-CT, the effectiveness of the PUI, PIPS, and SWEEPS activation methods in removing hard tissue debris accumulated in the root canal system of mandibular molars was compared. In distal canals, PIPS and PUI demonstrated similar cleaning performance. However, PIPS was found to be more effective than PUI, especially in the mesial root canals of lower molars. Anatomical differences, such as the shape, curvature, and diameter of the root canals, were found to be decisive in the results obtained. Furthermore, PIPS was determined to perform better than PUI in mesial roots containing an isthmus. Among all groups, SWEEPS was the method that removed the most hard tissue debris in both mesial and distal root canals, especially in mesial roots containing an isthmus (166).

4. Conclusion

Successful endodontic treatment depends on effective cleaning and disinfection of the root canal system, which cannot be achieved by mechanical instrumentation alone. The complex anatomy of root canals necessitates the use of irrigation activation methods to enhance the efficacy of irrigating solutions. Current evidence demonstrates that various activation technique, such as manual dynamic activation, sonic and ultrasonic systems, negative pressure devices, laser-assisted irrigation, and emerging multisonic technologies significantly improve irrigant penetration, debris removal, and microbial reduction. However, no single method has proven universally superior in all clinical situations. Therefore, irrigation activation should be selected based on canal anatomy, clinical requirements, and safety considerations rather than device preference alone. Combining appropriate irrigants with suitable activation strategies can enhance disinfection and contribute to improved clinical outcomes.

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