International Journal of Contemporary Dental and Medical Reviews (2014), Article ID 011214, 7 Pages

METHODOLOGIES

To evaluate the effect of two passive ultrasonic irrigation methods on removal of dentin debris from root canal systems using computational fluid dynamics study model

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Received 12.12. 2014;
Accepted 14.01. 2015

doi: 10.15713/ins.ijcdmr.20

How to cite this article:
Annil Dhingra, Panna Mangat, Anjali Miglani, Saurabh Kalkhande, Harkanwal Kaur Bhullar, "To evaluate the effect of two passive ultrasonic irrigation methods on removal of dentin debris from root canal systems using computational fluid dynamics study model," Int J Contemp Dent Med Rev, Vol. 2014, Article ID: 011214, 2014. doi: 10.15713/ins.ijcdmr.20

Abstract

Objectives: The aim was to evaluate the effect of passive ultrasonic irrigation (PUI), on removal of dentin debris from root canals comparing intermittent and continuous flow methods using a computational fluid dynamics (CFD) study model. **Methods:** A total of 75 freshly extracted single-rooted maxillary canines with mature apices were selected. The root canals were prepared to a master apical size of F4 and the teeth were then split longitudinally through the canal forming two halves. A standard groove was made and filled with dentin debris. Images of the groove were taken using a Nikon microscope at ×40 magnification without and with dentin debris. The two halves were re-assembled and teeth were divided into five groups and irrigated accordingly. Group 1: UI with continuous flow for 3.0 min, Group 2: UI with continuous flow for 1.5 min, Group 3: UI with intermittent flow for 3.0 min, Group 4: UI with intermittent flow for 1.5 min. Group 5: Syringe irrigation for 1 min. The root halves were separated and re-evaluated for the debris elimination after the irrigation protocol, for all the groups separately. The effect of time and method of PUI were compared. For the computational fluid analysis, GAMBIT 2.2 (Ansys) software was used for the mesh construction and the FLUENT 6.2 (Ansys) software to set the boundary conditions and the reconstruction of the canal. The velocity inlet boundary conditions were set for the entrance of the irrigant. The flow patterns and turbulence were graphically constructed. **Results:** The PUI and activation of sodium hypochlorite inside the root canal exhibited better debris removal than syringe irrigation both at 1% and 5% level of significance. However, the continuous irrigation methods were better at debris removal than intermittent irrigation flow methods. The time used for the various irrigation regimens had slight difference in the efficacy, which did not exhibit any statistical significance at 1% level of significance, but exhibited statistical significance at 5% level of significance. The CFD showed that the turbulence of flow of irrigant was dependent upon the inlet velocity and pressure of the irrigant. **Conclusion:** Within the limitations of this study, the debris removal from the canals was better with the PUI when compared with syringe irrigation. Passive continuous irrigation demonstrated better debris removal than the passive ultrasonic intermittent irrigation. In both methods, the effect of time did not have significant statistical difference. CFD removal depended on the turbulence that was affected by the velocity and pressure of the irrigant introduced and is a variable entity.

Keywords: Computational fluid dynamics, continuous irrigation, dentin debris, intermittent irrigation, passive ultrasonic irrigation

Introduction

Irrigation performs important physical and biological functions during endodontic therapy. Usually, the normal host defense mechanism takes care of any pathological activity. However to eliminate endodontic infections and for healing of periapical infections one requires a complete treatment regime of instrumentation, irrigation, medicaments, and fillings.[1] Irrigation helps the mechanical instrumentation techniques to eliminate microorganism, have antimicrobial properties, reduces friction and removes debris.[2] It helps in the better prognosis and a successful outcome of the treatment.[3] The effectiveness of irrigation relies on both the mechanical flushing action and the ability of irrigants to dissolve tissue and kill bacteria.[4] Passive ultrasonic irrigation (PUI) was first described by Weller *et al*. in 1980. The term passive describes the non-cutting action of the ultrasonically activated file. The energy is transmitted by means of ultrasonic waves and can induce acoustic streaming and cavitations of the irrigant. PUI can be an important tool for cleaning the root canal system when compared with traditional syringe irrigation.[5,6] PUI can be used in two different methods for irrigation, one being continuous and second intermittent. In the continuous method, the irrigant is continuously delivered into the canal which helps in the continuous activation of the irrigant and also a reduction of the irrigation time. In the intermittent flow method, the intermittent flow helps in the debris removal and pulpal dissolution in a more effective manner.[7]

The type of irrigation method also influences the volume and the time for which the irrigant action can take place.[8-11] The influence of irrigation time has an important role in deciding the efficacy of the irrigant. The time would also affect the temperature change in the canal during irrigation.

Computational fluid dynamics (CFD) is a method of mathematically modeling and computer simulation of various flow patterns and techniques. The fluid dynamics of an irrigant in the root canal involves the turbulent nature of the fluid. It is a branch of fluid dynamics that solves and analyzes problems involving fluid flow by means of computer-based simulations.[12,13]

Hence, the aim was to study the effect of PUI on the removal of dentin debris from root canals comparing intermittent and continuous flow methods using a CFD with following objectives:

1. To study the effect of PUI and its efficacy in the removal of dentin debris
2. To compare the efficiency of continuous and intermittent irrigating methods
3. To compare the efficiency of passive ultrasonic and syringe irrigation methods
4. To evaluate the turbulence of irrigants using a CFD model.

Methods

A total of 75 freshly extracted single-rooted maxillary canines with mature apices were selected. The diameter of the root canals was evaluated at different levels from the apex using radio-visiography. The teeth stored in physiological saline were then subjected to an ultrasound pre-treatment to remove the organic debris, followed by disinfection with 2.5% sodium chloride for 30 min. In addition, five freshly extracted canines were collected for the preparation of debris.

The diameter of the root canals was measured at 5 mm from the apex using a digital Vernier caliper and specimens presenting diameter smaller than 0.10 mm were discarded.

After sectioning teeth horizontally at 15 mm, standardized straight line access cavities were prepared using access cavity preparation kit with Endo Z bur followed by sodium hypochlorite and saline irrigation to remove the debris.

Working length (WL) determined using a 15 no. K file, which was inserted into the root canal until the tip of the file was just visible at the apical foramen. The stopper was adjusted to the reference point, and the file was withdrawn. WL was established by deducting 0.5 mm from this length; and registered as actual WL. Prepare the root canals up to the WL with universal rotary Protaper (Dentsply, Mallifer Ballaigus, Switzerland) finishing files to file F4 and splitted longitudinally through the canal to separate it into two halves.

A standard groove 2.0 mm in length, prepared in the split halves at a distance of 2.0 from the apex to 4.0 mm from the apex, 0.2 mm in width and 0.5 mm in depth was cut into one canal wall, to simulate a non-instrumented canal extension in the apical half.

Dentin debris is prepared by removing the enamel and cementum portion to expose the dentin surface that was then scrubbed on the Arkansas's stone for the preparation of the debris. The dentin debris was mixed with 2% sodium hypochlorite for 10 min and filled in each groove to reproduce a non-instrumented canal extension.

The dentin debris and the sectioned half of teeth with and without the debris were measured on an electronic weighing machine. To standardize the amount in each section 0.5 mg of dentin debris was introduced in each groove.

Grooves imaged using a Nikon microscope, E200 attached with a digital camera, Q Imagine Go- 3, at ×40 magnification with and without the dentin debris.

The two halves were re-assembled using orthodontic plastic bands and sticky wax. After reassembling the two root halves, the teeth were irrigated according to the different methods depending upon the group they belonged too. The 15 number ultrasonic K file was kept 1 mm short of the WL for UI.

The teeth were divided into five groups of fifteen maxillary canines in each group:

- Group 1: UI with a continuous flow for 3 min.
- Group 2: UI with a continuous flow for 1.5 min.
- Group 3: UI with intermittent flow for 3 min.

  The sodium hypochlorite in the root canal was activated ultrasonically for 1 min and the root canal was flushed every 20 s with 2 mL of 2% sodium hypochlorite with a 30G needle 1-2 mm short of the WL.

  Group 4: UI with intermittent flow for 1.5 min.

  The sodium hypochlorite in the root canal was activated ultrasonically for 1 min and the root canal was flushed every minute with 2 mL of 2% sodium hypochlorite with a 30G needle 1-2 mm short of the WL.
- Group 5: Syringe irrigation with 2 mL of 2% sodium hypochlorite with a 30G needle 1-2 mm short of the WL. Total irrigation time was 1 min.

The root halves were separated and evaluated for the dentin debris elimination from the groove after the irrigation protocol, for all the groups separately.

The effect of time and method of PUI were compared.

The quantity of debris in the groove before and after irrigation procedure was scored independently following the scores as per Mayer *et al.*;

- One, no debris or only isolated small particles were present.
- Two, minimal debris particles present in small clumps.
- Three, clumps of debris particles covered <50% of the canal wall.
- Four, clumps of debris particles covered more than 50% of the canal wall.
- Five, clumps of debris particles covered the canal wall.

CFD Analysis

Analysis of model geometry

The shape of the selected needle was obtained through a stereomicroscope. The needle dimensions were measured using a precision caliper.

The root canal was simulated as a geometrical frustum of cone 19 mm in length with a diameter of 0.45 mm at full WL and a diameter of 1.59 mm at the canal orifice, 19 mm coronally. The diameter of apical constriction was 0.3 mm and the diameter of apical foramen was 0.35 mm the needle was constructed to be placed 3 mm short of the WL, centered within the root canal.

Mesh generation

The pre-processor software GAMBIT 2.2 was used to build the three dimensional (3D) geometry and the mesh. A structural hexagonal mesh was constructed, with 1,279,856 cells.

Boundary conditions

The fluid was made to flow from the distal end of the needle and out from the orifice of the root canal. The velocity at inlet was 1, 6, 12, 24 and 36 m/s. The irrigant flow rate was 0.02, 0.14, 0.26, 0.53, 0.79 mL/s and Reynolds number was 177, 1063, 2126, 4253 and 6379 respectively. Turbulence intensity at the inlet was set to 5% and hydraulic diameter was defined as equal to the actual needle diameter. A pressure outlet boundary condition was imposed at the root canal orifice to allow flow of the irrigant, the atmospheric pressure was assumed at the outlet.

Sodium hypochlorite 2% aqueous solution was modeled as an incompressible Newtonian fluid, with a density equal to 1.04 am/cm cube and viscosity 0.986×10^{-3}.

Initial conditions

The domain was initialized with the irrigant at 50% of the inlet z-velocity, while x-velocity, y-velocity and gauge pressure were set to zero. Initial values for the turbulence kinetic energy and turbulence dissipation rate were calculated from the corresponding values at the needle inlet.

Solver setup

The commercial CFD code FLUENT 6.2 was used to set up and solve the problem and analyze the results. The numerical solution method uses a finite volume approach applied to an unconstructed mesh. A steady and isothermal flow was assumed. The governing time-averaged, 3D, incompressible Reynolds-Averaged-Navier-Equations were solved by a segregated implicit iterative solver.

The inlet flow rate of the needle was set as mass-flow-inlet at 0.1 g/s, and the turbulent intensity was set at 0%, which is identical to the *in vitro* model. At the orifice of the simulated canal, natural outflow boundary conditions were applied. The canal walls and apical foramen were considered rigid and impermeable, and a no-slip condition was applied at the walls.

The computation dynamics for different flow rates were compared. The turbulence kinetic energy and turbulence were calculated from the corresponding inlet values for each case. The flow patterns and turbulence were graphically constructed.

RESULTS

The mean score of debris remaining in each group after irrigation was 1.6 for Group 1 (passive continuous UI for 3.0 min group), 1.8 for Group 2 (passive continuous UI for 1.5 min group), 2.0 for Group 3 (passive intermittent UI for 3.0 min group), 3.07 for Group 4 (passive intermittent UI for 1.5 min group) and 3.73 for Group 5 (syringe irrigation for 1 min group). Hence, the remaining debris for Group 5 (that is, after syringe irrigation) was maximum [Table 1 and Graph 1].

The difference in the continuous and intermittent irrigation methods in debris removal at 3.0 min of irrigation exhibited a significant difference ($P < 0.05$). The continuous irrigation method at 1.5 min and the intermittent method for 1.5 min exhibited great difference in their efficacy with a value of 0.0098 at a level of significance of 5%.

The continuous irrigation for 3.0 min and 1.5 min exhibited minimal statistically significant difference in their efficacy for debris removal. However, the intermittent irrigation methods for 3.0 and 1.5 min exhibited greatly significant difference in the efficiency with 3.0 min of irrigation being more effective giving a statistical value of 0.260 at a level of significance of 5%.

The one-way ANOVA F-test shows a high significant difference among the different groups at 1% level of significance [Table 2].

Further, Karl-Pearson correlation coefficient shows a strong positive and significant correlation between Group 1 and Group 5 respectively at 0.1% level of significance [Table 3].

Table 1: Mean and variances of five different groups

Groups	Count	Sum	Average	Variance	SEM
Group 1 (3 min)	15	24	1.6	0.685714286	0.2138
Group 2 (1.5 min)	15	27	1.8	1.171428571	0.2795
Group 3 (3 min)	15	30	2	1.142857143	0.2760
Group 4 (1.5 min)	15	46	3.066666667	1.923809524	0.3581
Group 5 (1 min)	15	56	3.733333333	1.352380952	0.3003

SEM: Standard error mean

Table 2: One-way ANOVA-F table for significant difference among five groups

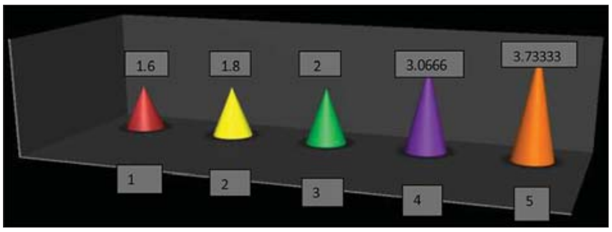
Source of variation	SS	DF	MS	*F*	*P*-value	*F* crit
Between groups	50.61333333	4	12.65333333	10.08042489	1.679E-06	5.20084703
Within groups	87.6666667	70	1.255238095		(*P*<0.001)	
Total	138.48	74				

SS: Sum of squares, MS: Mean square

Table 3: Karl-Pearson correlation coefficient among five groups

Groups	Group 1 (3 min)	Group 2 (1.5 min)	Group 3 (3 min)	Group 4 (1.5 min)	Group 5 (1 min)
Group 1 (3 min)	1				
Group 2 (1.5 min)	0.382546028*	1			
Group 3 (3 min)	0.080687153	0.308665499	1		
Group 4 (1.5 min)	0.286073192	0.19983995	0.048172031	1	
Group 5 (1 min)	0.489547434*	0.068099791	−0.05745482	0.056092365	1

*Values shows a high significant correlation at α=0.001 level of significance.



Graph 1: Average debris graph. The bar chart of average irrigation time for different groups

The independent *t*-test shows a significant difference in average debris score between Group 1 and 5, Group 2 and 5, Group 3 and 5 respectively at 0.1% level of significance. The results however exhibited no statistical difference for Group 4 and 5. Thus, the intermittent PUI done for 1.5 min exhibited non-statistical difference from the syringe irrigation group.

The Group 1 and 3 exhibited a difference in their efficacy which however did not have any statistical significance at a $P = 0.1\%$. Thus, the continuous and intermittent irrigation when done for 3 min exhibited a non-statistical difference in their efficacy.

Similarly, Group 2 and 4 exhibited a difference in their efficacy, which however exhibited statistically significant at a $P = 0.5\%$. Thus, the continuous and intermittent irrigation when done for 1.5 min exhibited statistically significant difference in their efficacy.

No significant statistical difference was observed in average debris score between Groups 1 and 2, that is the continuous PUI groups with a time difference of 1.5 min at a level of significance of 0.1%. Also at this level of significance even Group 3 and 4 that is the intermittent PUI groups with a difference of 1.5 min, exhibited no statistically significant results. However at the level of significance at 0.5% the difference of score between Group 3 and Group 4 were statistically significant. Thus, time did not play a significant role in the efficacy of the method of irrigation chosen for debris removal.

Further bar graph for average debris score shows the maximum debris remaining in Group 5 (control), while it was least in Group 1, respectively [Graph 2].

CFD

The CFD flow model exhibits the turbulence being highest at the apical one third of the root canal, implying the displacement magnitude of the tip is highest. It also proves that the flow of irrigant is from apical to the coronal.

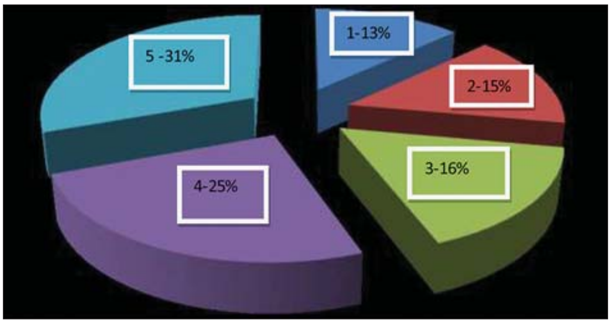
However the turbulence was dependent upon the inlet velocity and pressure of the irrigant flown, which is a variable entity. The higher the turbulence, the better will be the debris removal. In the present model, the inlet velocity was kept constant at 1 m/s to be able to evaluate the turbulence model. Hence, accordingly the turbulence was found maximum at the outlet [Graphs 3 and 4].

Discussion

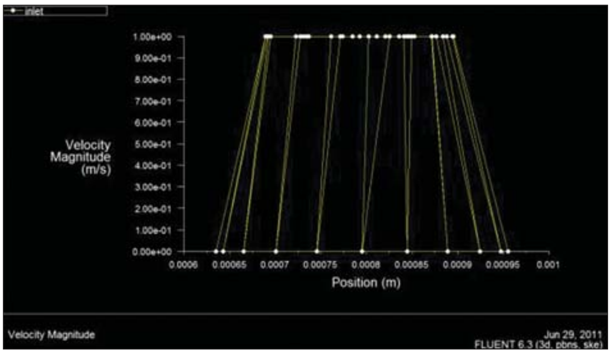
The success of endodontic treatment depends on the dentist's ability to clean and disinfect the complex canal system 3D, and then to fill and seal this space completely. Shaping of the canal opens this space to the action of an irrigant. Important requirements on the endodontic irrigant include properties such as antimicrobial activity, tissue-dissolving capability, and non-toxicity to periapical tissues. Penetration of irrigation material depend on several variables like root canal configuration, volume of irrigation solution, the type of irrigation solution, and the most important is a type of irrigation device.[3,4,14-16]

Two types of UI have been described in the literature. The first type is a combination of simultaneous ultrasonic instrumentation and UI. The second type, often referred to as PUI, operates without simultaneous instrumentation.

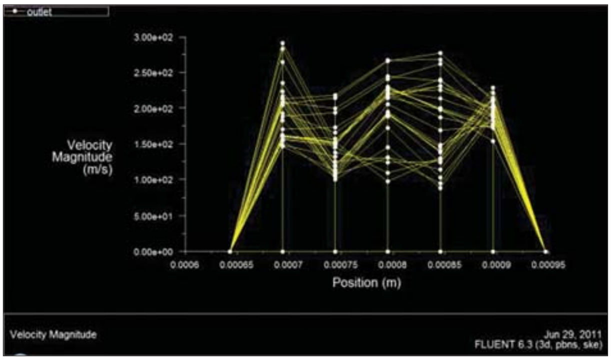
The latter induces acoustic streaming and cavitations of the irrigant.[5,6,14,16-18]



Graph 2: Remaining debris in the root canals



Graph 3: The velocity magnitude at inlet in the computational fluid dynamics model



Graph 4: The velocity magnitude at outlet in the computational

Acoustic streaming, as described by Ahmad *et al.*[11] has been shown to produce sufficient shear forces to dislodge debris in instrumented canals. When files were activated with ultrasonic energy in a passive manner, acoustic streaming was sufficient to produce significantly cleaner canals compared with hand filing alone.

According to Boutsioukis *et al.*, positioning of the needle closer to the WL improved the irrigant replacement in the apical part of the root canal but also led to increased mean pressure at the apical foramen, indicating an increased risk of irrigant extrusion toward the periapical tissue. The requirements of adequate irrigant replacement and reduced apical pressure appeared to contradict each other. From a clinical point of view, the prevention of extrusion should precede the requirement for adequate irrigant replacement and wall shear stress.[19] In the present study, a thinner gauge needle was used in accordance with the studies done earlier to reach the maximum distance up to the apical foramen. This not only simulated a clinical scenario but also removed the debris better during the syringe irrigation as the irrigant could flow to a maximum distance and with maximum turbulence.

In this study, the continuous and intermittent PUI methods were compared along with the syringe method of irrigation. It has been established that PUI methods are more effective than the syringe irrigation methods which is in accordance with many similar studies.[8,9,10,20-24]

According to a study done by Rodig *et al.* the irrigation devices including syringe irrigation, sonic irrigation and UI device, all were able to completely remove debris from artificial extensions in straight root canals. PUI removed significantly more debris than syringe irrigation or a sonically activated device. This was again in accordance with Sluis *et al.*[8] and Lee *et al.*[9] enforcing that UI gives better results than syringe irrigation.

The passive ultrasonic continuous and intermittent irrigation methods were compared and evaluated by various researchers.[6,7,21,25] During ultrasonic activation, a 25-gauge irrigation needle is used instead of endosonic files. This enables ultrasonic activation to be performed at the maximum power setting without causing needle breakage. The unique feature of this needle-holding adapter is that the needle is simultaneously activated by the ultrasonic handpiece while an irrigant is delivered from intravenous tubing connected via a Luer-lok to an irrigation-delivering syringe. The irrigant can thus be delivered apically through the needle under a continuous flow instead of being intermittently replenished from the coronal access opening. The study done confirmed with the earlier found results and found continuous irrigation to be a more efficient method than intermittent method of PUI. However, the effect of time was insignificant in the present study, which was in accordance with certain studies[7,21] but varied from studies.[26] This could be due to the amount of irrigant used in the specified time, which was kept a variable entity here.

The continuous flow of irrigant helped in the activation of the sodium hypochlorite used and thus better debridement and disinfection of the canal.[3,21,27] Sodium hypochlorite has proved over the ages its efficacy and was thus utilized as a standard in the above study.

The needle was chosen of a 30 gauge for the maxillary canines owing to the wider dimensions of the canal, and the depth of needle required being 2-3 mm less of the total length.[26,28,29,30] Side vented needles have proved better efficacy[26,31] and were thus used in the present study.

CFD is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows.

It is a new approach in endodontic research to improve our understanding of fluid dynamics in the special anatomic environment of the root canal. Fluid flow is commonly studied in 1 of 3 ways: Experimental fluid dynamics, theoretic fluid dynamics, and CFD.

Some of the goals of CFD studies in endodontics are to improve needle-tip design for effective and safe delivery of the irrigant and to optimize the exchange of irrigating solutions in the peripheral parts of the canal system.

The CFD model exhibited the turbulent flow exhibited by the irrigants in the root canal at the various velocities and pressure. The turbulence was maximum at the apical one-third thus proving the fact that the apical displacement of the irrigant at the apical one-third is of utmost importance for an efficient cleaning and debris removal in the root canals. However, Boutsioukis *et al*.[32] said that in such studies it is assumed that the root canal has smooth walls and the needle is accurately placed in the center of the canal in the CFD model which is inconsistent with real dentine anatomy. Although McCabe *et al*. in 2004 said that wall roughness is expected to have a limited effect on pressure drop as long as the flow remains laminar, but it may induce vorticity or even turbulence in the flow (Azuma & Hoshino 1985).

Boutsioukis *et al*.[31] from the apical stop stated that irrigant replacement reached the WL only when the side-vented needle was placed at 1 mm; therefore, it seems reasonable to suggest that this needle should be positioned within 1 mm from the WL if possible. Additional safety against irrigant extrusion in case of binding in the root canal is provided by the blind end of the side-vented needle.

In the present study, the side-vented needle was chosen keeping in mind the studies which prove their efficacy and less chances of extrusion of the debris perapically. The needles were kept at a distance of 3 mm from the WL to bring about the maximum efficacy of the irrigant with the turbulent flow and avoid the extrusion of the debris. Also, as the inlet velocity was kept constant to measure the turbulence of the irrigation model. The turbulence was found maximum at the outlet which reinforces the already proven fact that the needle should be loose in the canal and kept short of the WL.

Conclusion

Within the experimental conditions, the results exhibit that the PUI method is an efficient method of irrigation, which helps in removing debris from the root canals effectively. The continuous method of PUI proves to be a comparatively better method of irrigating the canals than the intermittent passive irrigation method.

The PUI method proved to be more efficient and a better method than syringe irrigation.

The CFD modeling of the root canal exhibited that more the pressure the more will be the turbulence which may however even cause extrusion of the irrigant. Furthermore, the more the turbulence, the better will be the removal of debris from the root canal. Therefore, a balance needs to be maintained for the best irrigation results between the pressure and desired turbulence.

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