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Research Paper

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Irrigant Flow in Micro-Computed Tomography Scanned Root Canals Using Computational Fluid Dynamics Model

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The aim of this study was to evaluate the irrigant flow pattern of a hypodermic needle; in Micro-Computed Tomography (MCT) scanned root canals prepared using Reciproc[®] files at two different levels using a Computational Fluid Dynamics (CFD) model. Two lower incisors prepared with Reciproc[®] rotary files sized R 25 and 50, underwent MCT scanning to create 3-dimensional root canal models. A computational model of a 30 G hypodermic needle was then positioned at 3 and 5 mm from the apex in each root canal model. Irrigant flow pattern, velocity and mean apical pressure at 1 mm from the apices were evaluated using commercial CFD software, Star CCM+. The irrigant produced a high velocity jet, reaching 5.8 m sec⁻¹, at the needle outlet and created multiple vortices near the canal wall before exiting at the canal orifice. Mean apical pressure and velocity recorded for R 25/3 mm (7.77 kPa/0.235 m sec⁻¹), for R 25/5 mm (4.34 kPa/0.001 m sec⁻¹), for R 50/3 mm (7.89 kPa/0.005 m sec⁻¹) and R 50/5 mm (4.49 kPa/0.0001 m sec⁻¹). Close proximity of the needle to the apex produced higher mean apical pressure; meanwhile, larger apical preparation sizes produced lower velocity of irrigant. It was observed that within the same canal, irrigant flow patterns were similar for both needle levels. Needle positions and apical preparation sizes were found affecting the apical pressure and velocity. The CFD simulations in MCT scanned root canals were clinically significant.

Key words: Tooth root, sodium hypochlorite, stimulation, flow pattern, hypodermic needle

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INTRODUCTION

Delivery of sodium hypochlorite irrigant in the root canal system has been routinely used with needle and syringe technique. One limiting factor is the inability of irrigant to reach the apical third of the root apex. This because the area is too narrow and therefore irrigant replacement cannot take place effectively and be in contact with the microorganisms and dentine debris present in the canal (Gulabivala *et al.*, 2005). Furthermore, this will have to be carried out with minimal apical pressure to prevent tissue damage due to apical extrusion.

Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that describes fluid flow and analysis by means of physical and chemical phenomena using mathematical modeling and computer simulation. Analysis of simulated root canal irrigant flow has successfully been reported and has the potential to serve as a platform for the study of root canal irrigation (Haapasalo *et al.*, 2010). So far all the CFD studies (Boutsoukis *et al.*, 2010a, b, c) have used simulated root canals and modeled irrigation needles to provide details of the flow pattern which include the velocity field, sheer stress and pressure in areas where experimental measurements are difficult to perform. The use of Micro-Computed Tomography (MCT) in endodontics is rapidly increasing and used to analyze the exact morphology of the intracanal thoroughly. It offers reproducible data of the natural tooth in 3-dimensional view, which can be transferred into readable data by CFD model. This should provide a realistic representation of irrigant flow in natural root canal and comparison between the simulated data can be made.

This study attempted to investigate the irrigant flow delivered through a hypodermic needle in MCT scanned root canal that has been prepared with a single endodontic file; Reciproc® using the CFD model. Here, two different apical size preparations R 25 and 50 were compared at two different needle insertion level. The aim of this study was to compare the irrigant flow effect delivered through hypodermic needles in two different apical size preparations at 2 different depths using the computational fluid dynamics model.

MATERIALS AND METHODS

Teeth selection and root canals preparation: Access cavity was performed to the 2 lower incisors. A size #10 K-flexo files was used to confirm the patency of root canals and Working Length (WL) were recorded respectively. Each tooth was prepared with either Reciproc® rotary files R 25 with 08 taper and apical diameter of 0.25 mm or R 50 with 05 taper and 0.50 mm apical diameter.

Micro-computer tomography scanning: The prepared teeth were sent for MCT scanning at resolution of 35 µm. The images of root canal were reconstructed into 3-dimensional

view in stereolithography format. The scanned root canals were further repaired using Hypermesh® software to correct the defects which occurred during MCT scanning.

Construction of a hypodermic needle model and positioning into root canal model: A computational simulated model of a 30 G hypodermic needle was generated using Catia® software. For each root canal, the model of the needle was positioned at two different levels of canal depths, which were 3 and 5 mm from the apex.

Computational fluid dynamics simulation using star ccm+® software: The model of the needle and the 2 scanned root canals were imported into Star CCM+® software to perform CFD simulation. Polyhedral mesh was selected as framework. No slip boundary conditions were applied to the solid surfaces, which were the walls of the canal and of the needle, under the hypothesis of rigid, smooth and impermeable walls. The fluid flows out off the distal end of the needle, towards the orifice of the root canal. The irrigation solution, sodium hypochlorite 1% aqueous solution, was modelled as an incompressible, Newtonian fluid, with density of 1.04 g cm^{-3} and viscosity of 0.99×10^{-3} . Laminar model was used as the reynold numbers calculated denoted laminar flow models.

RESULTS

For all 4 simulations which were R 25/3, R 25/5, R 50/3 and R 50/5 mm, steady flow of the irrigant was observed after 500 iteration period of CFD simulation. The irrigant flow pattern in the apical part of the canal was similar in the 3 and 5 mm levels.

To provide a qualitative visualization of the flow fields, streamlines were generated for the needle inlet as in Fig. 1 (A₁, B₁) and Fig. 2 (C₁, D₁). The highest pressure was at the needle opening (4.47 kPa) as retrieved by the CFD program. It then gradually decreased as fluid dispersed out into the root canal as in Fig. 1 (A₂, B₂) and Fig. 2 (C₂, D₂). Pressure at the apical third of canal was lower, 4.43 kPa for R 25 and 4.49 kPa for R 50 when the needle was 5 mm away from the apex compared to 3 mm (Fig. 3). The readings were 7.67 kPa for R 25 and 7.89 kPa for R50 (Table 1).

The highest velocity was observed at the needle opening in figure velocity A₃ and B₃ represented as the red colour spectrum corresponding to 6.0 m sec^{-1} scale. The velocity then gradually decreased as it exited from the needle opening, represented as the light and dark blue area in the same figures.

Table 1: Velocity and pressure at 1 mm from the apex

Preparation size	Level of needle (mm)	Velocity (m sec ⁻¹)	Pressure (kPa)
0.25/.08	3	2.35×10^{-1}	7.67
0.50/.05	3	5.04×10^{-3}	7.89
0.25/.08	5	1.05×10^{-1}	4.43
0.50/.05	5	1.55×10^{-4}	4.49

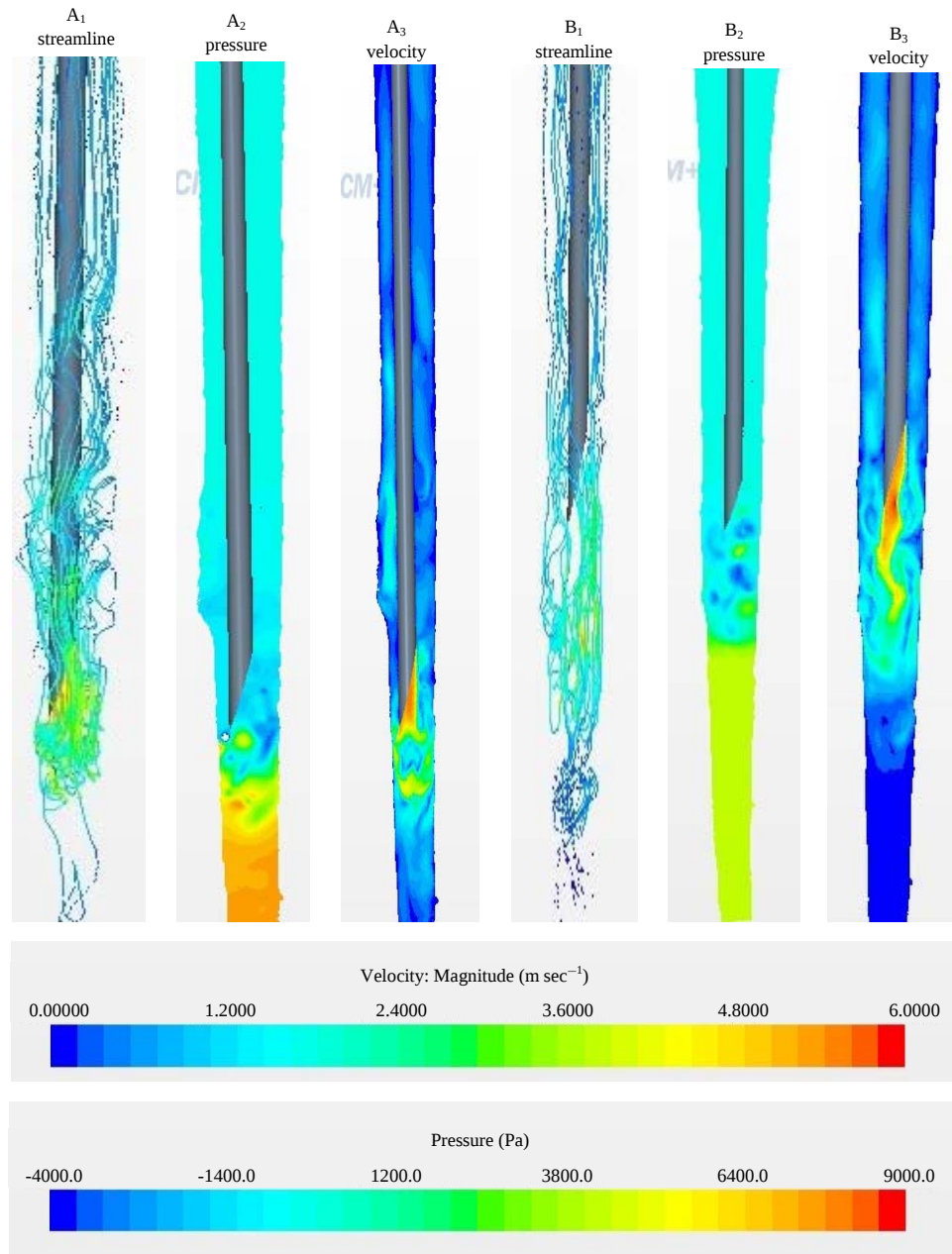


Fig. 1: Irrigant flow pattern of streamline, pressure and velocity at 3 mm (A₁, A₂, A₃) compared to 5 mm (B₁, B₂, B₃) level using Reciproc® R 25/08

Laminar flows were observed in the needle lumen in high pressure and gradually become transitional and turbulent flow as it exited the needle opening. The fluid was directed towards apical part of root canal and gradually flows in reverse direction as curved streamlines towards the canal orifice. Interferences represented as swirl of vortices were observed at the region between needle outlet and canal wall.

DISCUSSION

Irrigant flow is a substantial finding as it determined irrigant replacement ability, development of apical pressure

and velocity of the prepared root canal. With CFD simulations, flow pattern provided a physical explanation for the calculated values mentioned in the result section.

There are several factors that influenced the apical pressure, velocity and fluid replacement in a prepared root canal (Boutsioukis *et al.*, 2010a-e). The factors included: needle insertion level, apical size preparation, root canal taper.

Positioning of the needle close to the working length improved the irrigant replacement in the apical part of the root canal but also led to increased mean pressure at the apical foremen, indicating an increased risk of irrigant extrusion

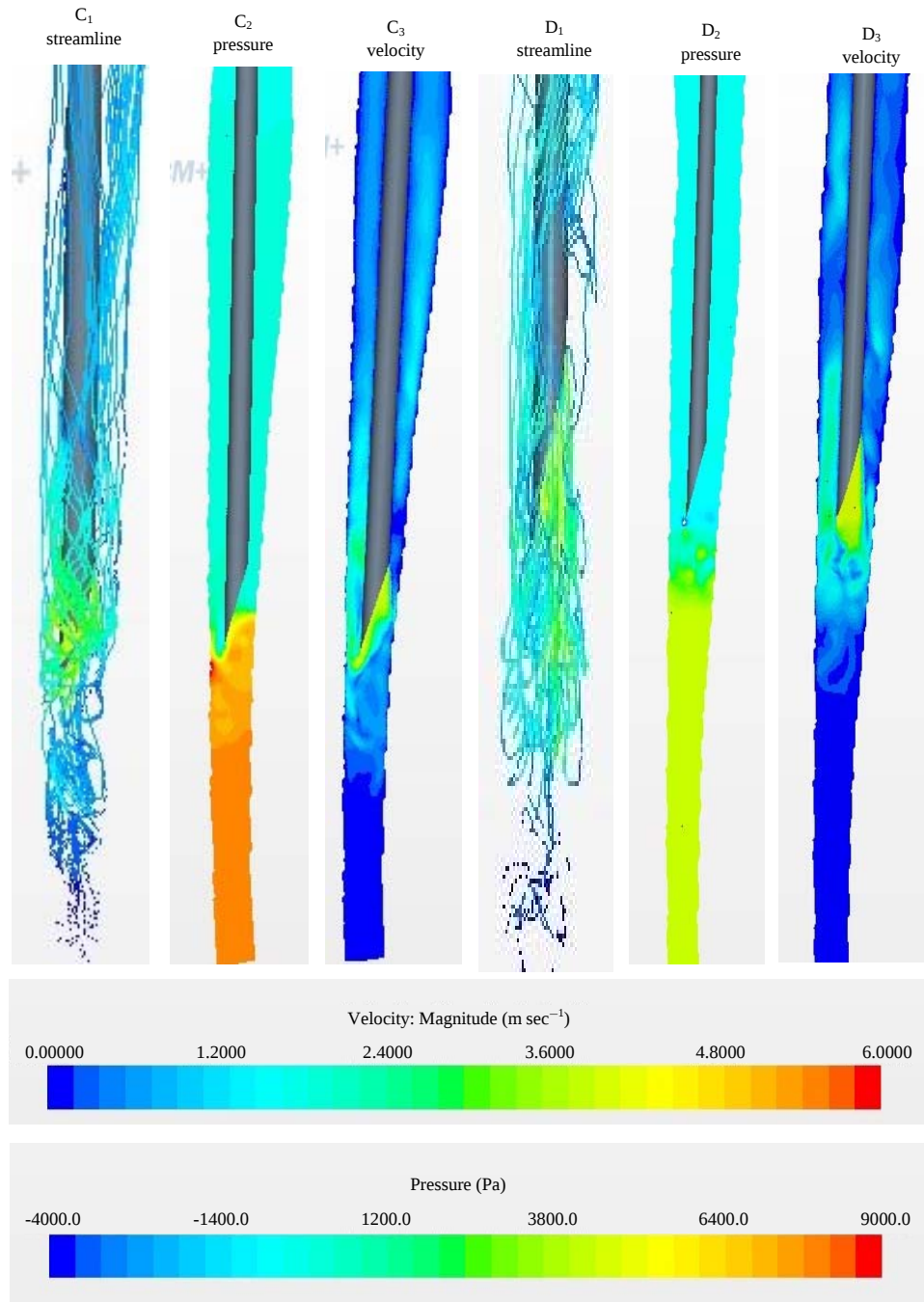


Fig. 2: Irrigant flow pattern of streamline, pressure and velocity at 3 mm (C_1 , C_2 , C_3) compared to 5 mm (D_1 , D_2 , D_3) level using Reciproc® R 50/05

towards 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 sheared stresses. However, because there was no definite evidence on the minimum irrigant pressure that leads to extrusion, it can only be estimated by comparison between different needle insertion depths. The further away the needle was positioned, from the

WL, the less apical pressure developed. Furthermore, the irrigant exchange was also less efficient and the wall shear stress was lower. A reasonable position would be to place 2-3 mm which could still ensure adequate irrigant exchange. The optimal needle depth might be influenced by canal size and taper and the presence of the curvature.

The effects of needle insertion levels on fluid flow had also been proven in our study. The pressure when needle was at 3 mm is 7.67 kPa (R 25) and 7.89 kPa (R 50) which were

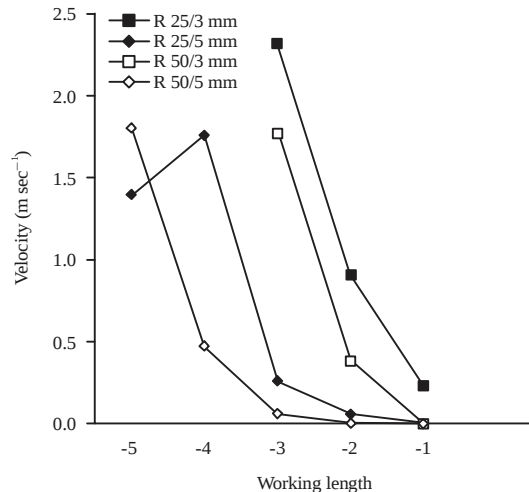


Fig. 3: Comparison between irrigant velocity vs different needle levels (WL) in canal prepared with R 25 and 50

higher compared to 4.43 kPa (R 25) and 4.49 kPa (R 50) at 5 mm. This was because the highest pressure at the needle tip was closer to the apex at 3 mm compared to 5 mm. This improved efficiency in irrigation. However, the risk of apical extrusion increases. In conclusion, the needle insertion depths were found to affect the extent of irrigant replacement and pressure at the apical third of root canal.

Increasing the preparation size resulted in more efficient irrigant replacement. With an increase in preparation size, it allowed penetration of the needle closer to WL and has a direct effect in irrigant flow (Chow, 1983; Albrecht *et al.*, 2004; Usman *et al.*, 2004; Falk and Sedgley, 2005; Hsien *et al.*, 2007). The larger the apical preparation size, the wider the distribution of wall sheared stress. However, the maximum sheared stress that gradually decreased. Shearing stress had a direct effect on irrigation efficiency. Higher shear stress improved irrigation. Therefore, over enlargement of the root canal further than a certain size reduced shear stress and hence, also reduced the debridement efficacy of irrigation. Differences identified in irrigant flow as a result of preparation size highlighted the importance of the space available around the needle for the reverse flow of the irrigant towards the canal orifice. An increase in the preparation size caused a decrease in average velocity and apical pressure and increase in irrigant replacement in the apical third of root canal.

This study found that at the same needle insertion depths, the velocity was lower in the bigger apical preparation. These findings were similar with previous studies. However, there was slight increase in pressure in larger prepared canal. At 3 mm, pressure was 7.67 kPa (R 25) compared to R 50 which was 7.89 kPa. At 5 mm, pressure was 4.43 kPa (R 25) lower than 4.49 kPa (R 50). This contradicted with the previous studies that stated larger apical preparation had lower pressure. This could be explained by the presence of vortices between the needle wall and the canal wall which might cause

differences in pressure. There were few vortices found at the same fluid field. The magnitude of the merged vortex was the sum of the circulation of the constituent vortices. Therefore, this explained the lower pressure obtained in the larger apical size preparation.

Increasing the taper of the root canal resulted in improved debridement during irrigation. It has direct effect on irrigant flow resulting in more efficient replacement and debridement in the apical part of root canal apart from allowing penetration of needle closer to WL (Albrecht *et al.*, 2004; Huang *et al.*, 2008). Therefore, an increase in root canal taper had improved irrigant replacement and wall shear stress whilst reducing the risk of irrigant extrusion. However, increasing the taper to a certain value might in fact decrease the debridement efficacy of irrigation because the average velocity and the wall shear stress decreases (Boutsoukakis *et al.*, 2010b).

Debridement efficacy of irrigation depended on average velocity and wall shear stress. It had direct effect on irrigant flow resulting in more efficient replacement in the apical part of root canal. This was significant in this study as it was found that the larger taper canal had a higher velocity. At 3 mm, R 25 with taper of 08 (8%) had 0.235 m sec^{-1} compared to taper 05 (5%) with lower velocity which was $5.04 \times 10^{-4} \text{ m sec}^{-1}$. The same applied in R 50 where velocity was $1.05 \times 10^{-2} \text{ m sec}^{-1}$ higher than $1.55 \times 10^{-4} \text{ m sec}^{-1}$ at 5 mm.

Future studies with 3-dimensional models based on real root canals of different shapes and high resolution micro-computed tomography scans were needed to better understand the effect of canal wall surface texture to fluid flow (Shen *et al.*, 2010). In this study, we have opted to use 3-dimensional images from micro-computed tomography at $35 \mu\text{m}$ to have an accurate representation of the root canal. Assumption and images of previous studies were based on simulated canals which had smooth impermeable walls. This might be true up to a certain magnification only. In this study, we found that the wall of the root canal, even after instrumentation, irregular surfaces were still evident. This proved that micro flow and fluid dynamics are more varied and complex than the hypothesis from previous studies. The velocity and pressure may vary depending on the path the fluids takes and the point where it hits the canal wall. Vortices were also present and may influence the pressure and velocity. In conclusion, fluid dynamics in a micro-computed tomography scanned natural tooth, are more complex due to the presence of irregular surfaces in the internal surface of the prepared canal. Needle insertion levels, apical size preparation and tapering influenced irrigant flow pattern, pressure and velocity and fluid replacement. This had significant effect in the irrigation efficacy in the root canal system.

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