Odontology
https://doi.org/10.1007/s10266-024-01028-7

ORIGINAL ARTICLE

Computational fluid dynamics analysis of conventional irrigation and the combination with adjuvant suction cannulas in human molars with isthmus communication

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Received: 30 September 2024 / Accepted: 13 November 2024

Abstract
This study evaluated CFD key irrigation parameters (flow pattern, irrigant velocity, wall shear stress and apical pressure) of conventional irrigation with positive pressure side-vented (SV) needle and the combination of different suction cannulas in the mesial root of human mandibular molars with 2 independent root canals and isthmus communication. A micro-CT scan of a molar presenting 2 root canals and an isthmus communication in the mesial root was obtained for computational analysis after root canal preparation and geometric reconstruction. Computational models of a 30G SV needle and three different suction cannulas (EndoVac Macro cannula (MaC), Surgitip (SURG) and iNP needle (iNP)) were designed. Four different simulations were carried out: simulation SV (SV needle located at 2.5 mm from working length (WL) in mesiolingual root canal (ML)), simulations SV-iNP, SV-SURG and SV-MaC (SV needle in ML plus the respective suction cannula placed at 7.5 mm from WL in mesiobuccal root canal). Key magnitudes of irrigation were compared with CFD. The irrigant solution did not enter the isthmus in SV simulation. Simulations SV-iNP, SV-SURG and SV-MaC exhibited a better performance in shear stress and apical pressure. Fluid flow did not reach the apical millimeters of the main root canal, but substantial flow and shear stress was observed in the isthmus in SV-SURG and SV-MaC simulations. The use of suction cannulas aids conventional irrigation in roots with 2 independent root canals and isthmus communication by improving irrigant flow, increasing shear stress in the root canal walls and isthmus, and slightly decreasing apical pressure.

Keywords Endodontics · Irrigation · Isthmus · MicroCt · CFD · Suction cannula

Introduction

Relevant endodontic treatment goals are to optimize root canal disinfection and to prevent re-infection [1]. For an optimal outcome of the endodontic treatment, bacterial populations within the root canal should be ideally eliminated or at least significantly reduced to levels that are compatible with periradicular tissue healing [2]. Sodium hypochlorite (NaOCl) is the most extended irrigation solution in endodontics due to its tissue dissolving capacity and antimicrobial properties [3]; however, the complex intricacies present in the root canal system makes irrigant penetration challenging and this is one of the most important causes of failure [4, 5]. In fact, 9% of failures after non-surgical root canal treatment are due to anatomical complexities [6]. Among the common irregularities, an isthmus (also known as transverse anastomosis) is an anatomical variant defined as a narrow, ribbon-shaped communication between 2 root canals that contains pulp tissue [7, 8]. Isthmuses are common reservoirs for tissue and bacteria and poorly accessible to root canal instruments. It has been reported a prevalence of isthmuses close to 55% with main location in the middle and apical thirds of the mesial root of first mandibular molars [9] and this percentage increased to 85% for isthmuses located in the apical 5 mm of the mesial root when microcomputed tomography (micro-CT) was used [10].

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Published online: 28 November 2024

Final irrigation protocols aim to clean the canal complexities that are not addressed with shaping procedures [11] even when root canal instrumentation is performed in the presence of irrigant solutions [12]. In fact, the irregular nature of the isthmus may also jeopardize irrigant efficacy resulting in ineffective dissolution of hard and soft tissue remnants and microorganisms [13].

Adcock *et al.* demonstrated that neither irrigation with needles nor a continuous ultrasonic irrigation could eliminate debris of the apical portion of narrow isthmuses in the mesial roots of mandibular first molars [14].

Computational fluid dynamics (CFD) has been used in endodontics to observe the behavior of irrigant solutions and have been essential to understand the irrigation key magnitudes since 2009 [15–17]. CFD is a branch of fluid mechanics that analyses fluid flow by means of computer-based simulations [18]. Compared to *in vitro* studies, CFD allows the understanding of important parameters that other methodologies cannot provide, including the flow pattern, the shear stress produced in the walls of the root canal or the apical pressure exerted during the irrigation process.

Thomas *et al.* in 2014 showed promising results suggesting a modified EndoVac (Discus Dental, Culver City, CA) irrigation protocol combined with conventional needle irrigation for the mesial roots of mandibular molars with 2 root canals and an isthmus communication. This technique performed significantly better than the other irrigating systems in achieving canal isthmus cleanliness [19] and inspired the present study to fully understand the key parameters of irrigation when conventional needle positive pressure irrigation is used in one canal combined with a suction cannula in a second canal of the same root with an isthmus communication. Moreover, apart from EndoVac (Discus Dental, Culver City, CA), simpler cannulas could also obtain comparable effect.

Furthermore, the combination of CFD and micro-CT is a validated method to analyze the behavior of irrigants and irrigation key magnitudes inside the root canal of real human teeth with complex anatomies [20, 21].

Therefore, the purpose of this study was to evaluate with CFD the key aspects of irrigation (flow pattern, irrigant velocity, wall shear stress and apical pressure) of conventional irrigation with side-vented needle (SV) with and without the combination of different suction cannulas in a mesial root of human mandibular molars with 2 independent root canals and isthmus communication.

Materials and methods

Tooth selection, root canal preparation and geometric reconstruction of the sample

Five extracted mandibular human first molars were obtained and scanned using a micro-CT scanner (XT-H-160; Nikon, Leuven, Belgium) with an isotropic voxel size of 30 µm. The mesial root of 1 mandibular molar presenting 2 root canals and an isthmus communication was selected. The base of the isthmus was located at 3.8 mm from the apex and had a width of 0.85 mm.

Access cavity preparation was performed in the molar with a diamond bur (number 856, Komet Dental GmBH, Lemgo, Germany) and root canals scouted with a size #10 K-file (Dentsply Sirona Endodontics, Ballaigues, Switzerland). Working length (WL) was determined by inserting a #10 K-file through the major foramen and withdrawing it 1.0 mm. A glide path preparation was carried out to a size #15 K-file up to the WL and the root canal preparation was performed with Rotate rotary system (VDW, Munich, Germany) following manufacturer´s directions per use up to a #30.04 instrument. Root canal irrigation was performed with 10 mL of 5.25% solution of sodium hypochlorite (NaOCl) throughout the shaping procedure and a final rinse with 1 mL 17% EDTA followed by NaOCl was performed for each canal. Irrigation was performed with two 3 mL syringes and 27 G needles (Monojet; Tyco Healthcare, Mansfield, MA) placed 3 mm from WL or of its binding point. After root canal preparation, the tooth was scanned again with micro-CT and a total of 1001 cross-sectional slice images (TIFF format) were obtained with a resolution of 20 µm. The 3-dimensional (3D) root canal models were segmented, reconstructed, and exported in STL format with MeshMixer (MeshMixer, Autodesk, San Francisco, CA, USA). STL showed that the files only conformed the main canals and the isthmuses remained intact.

Geometric modeling of irrigation needle and suction cannulas

A 30G endodontic irrigation needle and three different suction cannulas were designed. SV needle was designed following international standard ISO 9626:2016 specifications for 0.3 mm (30G; external diameter = 300 µm; internal diameter = 190 µm) and the dimensions of Maxi-Probe needle (Dentsply/Tulsa Dental, York, PA) were assumed to design the vent (0.5 mm side-vent located 1mm away from the tip). Three suction cannulas were designed based on their measurements and specifications:

EndoVac Macro cannula (MaC) (Kerr Dental, Orange, CA, United States), Surgitip Endo cannula (Coltene, Altstätten, Switzerland) (SURG) and iNP needle (Mixnus, Nagano, Japan) (iNP). Both MaC and SURG are plastic cannulas, while iNP is metallic. Specific tip dimensions for internal/external diameters are 0.50/0.55 mm, 0.35/0.60 mm and 0.26/0.35 mm respectively for MaC, SURG and iNP [22] .

A digital model of each needle and cannula were built with computer-aided 3D CAD design software (SolidWorks 2016 x64 Edition, Dassault Systèmes, Paris, France). The 3D models of the teeth were imported with Geomagic 3D Systems software (Rock Hill, SC, United States), prepared and converted to IGES format. The distal roots were removed to improve CPU performance.

Design modeling and meshing

Four different simulations were carried out. One of them simulated a conventional irrigation model without an adjuvant suction cannula (SV); while the other three included an adjuvant suction cannula in the other root canal (SV-MaC, SV-SURG and SV-iNP). To determine the position of the needle and cannulas in the simulations, the length that they reached passively was calculated by inserting them inside the prepared root canals of the natural teeth to improve the reliability of the study and provide a feasible clinical translation. The distance to WL was measured. The largest suction cannula (SURG) advanced passively to 7.5 mm coronal to WL in the mesiobuccal (MB) root canal and the positive pressure needle advanced to at 2.5 mm from WL in the mesiolingual (ML) root canal. The position was confirmed radiographically. For this reason, the positive pressure needle was placed at 2.5 mm from WL and all suction cannulas were placed at this distance (7.5 mm from WL) in MB root canal in order to standardize the simulations as follows: simulation SV (the SV needle was located in the ML root canal and no suction cannula was used), simulations SV-iNP, SV-SURG and SV-MaC (apart from the SV needle in the ML root canal, a suction cannula was placed in the MB canal) (Fig. 1).

The finite volume discretization was performed with ANSYS 18.2 (Fluent Inc., Lebanon, NH, USA). Meshes with close to 3 million quadratic tetrahedral elements were obtained. The quality of the mesh was ascertained gathering within normal limits of skewness and orthogonality.

Boundary conditions and numerical simulation

The root canal walls, the needle and cannulas were considered rigid and impermeable surfaces. To reproduce NaOCl characteristics, the fluid was incompressible, Newtonian, homogeneous and isothermal with 1.04 g/cm^3 density and 0.9998 kg/m^3 viscosity. Fluid was delivered in the corono-apical direction of the needle with a 0.1 g/s (6 ml/min) flow, and the outlet was set at environmental pressure in the coronal access of the root canal. The suction power for the three cannulas was set at 130 mb and the effect of gravitational acceleration at 9.81 m/s^2 during the fluid simulation.

Numerical simulations were then run with the CFD extension of ANSYS 18.2 (ANSYS Fluent, Canonsburg, PA, USA). Computer hardware specifications was Dell Intel Xeon® (CPU ES 2680 0 2x2.70GHz, 32GBRAM memory and a 64 Bits operative system) server.

The transient flow simulation model and parameters for backflow turbulent intensity and viscosity ratio were adopted from a previous study [20, 21].

By post-processing the results, the fluid pattern and velocity, wall shear stress distribution, and apical pressure were analyzed. Streamlines and velocity maps revealed the direction and magnitude of the flow. Shear stress and apical pressure were compared among simulations. Shear stress and apical pressure were contrasted among simulations to indirectly analyze cleaning efficiency.

Results

Figure 2 illustrates velocities, streamlines, shear stresses and apical pressures for all simulations (SV, SV-iNP, SV-SURG and SV-MaC). A colored scale was standardized for the

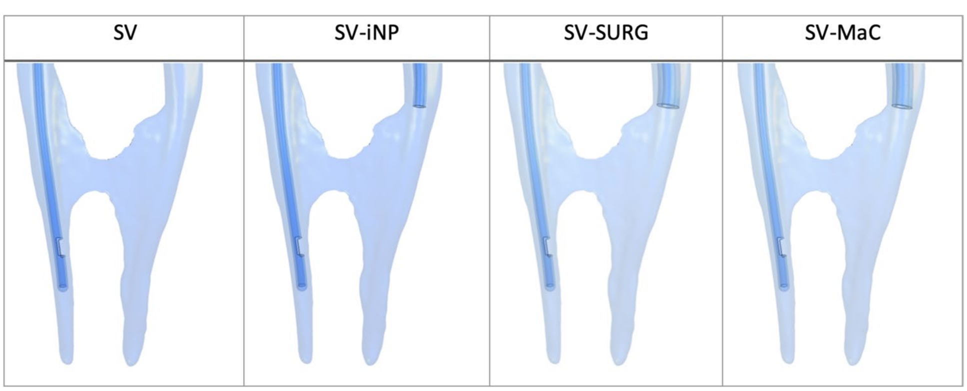

Fig. 1 CAD models for the four simulations: SV, SV-iNP, SV-SURG and SV-MaC

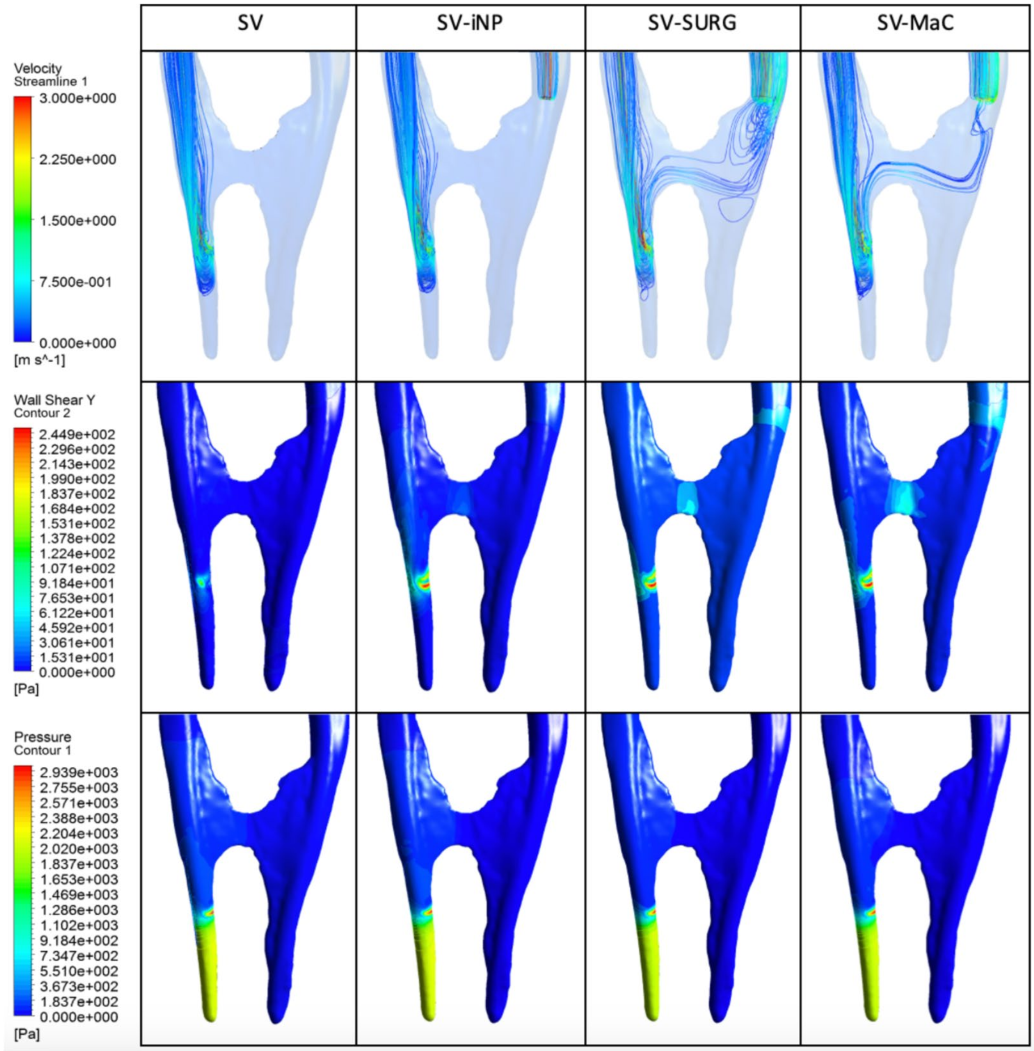

Fig. 2 Velocities, streamlines, shear stresses and apical pressures for the four simulations: SV, SV-iNP, SV-SURG and SV-MaC

Table 1 Maximum values of shear stress in the isthmus and in ML root canal, as well as apical pressure in ML root canal for the four simulations: SV, SV-iNP, SV-SURG and SV-MaC

	Isthmus	ML root canal	
	Shear stress (mmHg)	Shear stress (mmHg)	Apical pressure (mmHg)
SV	0.04	1.13	15.32
SV-iNP	0.14	2.07	15.23
SV-SURG	0.48	1.99	15.13
SV-MaC	0.56	2.00	14.87

interpretation of all parameters using blue, green and yellow-orange-red colors to represent respectively low, medium and high values. Table 1 shows maximum values of shear stress and apical pressures for all simulations in the ML root canal and inside the isthmus.

In general, the use of irrigation needles alone did not allow the irrigant solution to enter the isthmus, while the use of adjuvant suction did. Particularly, the flow reached SURG and MaC cannulas when located in the MB root canal. At the same time, the fluid flow did not reach the apical millimeters of the root canals in any of the simulations. The use of any adjuvant suction increased the shear stress in the main root canal and slightly decreased apical pressure values. As shown in Table 1, shear stress values in the isthmus varied in the different simulations up to nearly ten times higher for certain cannulas.

SV simulation

The fluid flow neither reached the isthmus nor reached the apical millimeters of the root canals. Medium and maximum velocity values were presented at the exit of the needle in the main canal. Highest maximum shear stress values

(1.13 mmHg) were the lowest from all simulations and only reached only near the exit of the needle. Consequently, apart from this area, wall shear stress was almost null in the rest of the root canal and in the isthmus.

SV with adjuvant suction in a MB root canal

The use of suction cannulas increased the irrigant fluid flow in the isthmus and in the ML root canal. SV-iNP simulation shows negligible fluid flow and shear stress values in the isthmus (Fig.2). Substantial flow was observed for SV- SURG and SV-MaC, reaching 0.48 and 0.56 mmHg shear stress values respectively in the isthmus. At the same time, fluid flow did not reach the apical millimeters in any root canal, but the greatest fluid flow in the MB canal was observed in SV-SURG. As shown in Table 1, shear stress did not vary among SV-iNP, SV- SURG and SV-MaC in the main root canal; but it was higher than in SV simulation.

Discussion

One of the most important causes of failure in endodontic treatment is the ineffective debridement and cleansing due to the complex intricacies of root canal systems [4]. Specifically, isthmuses are common reservoirs for tissue and bacteria, mainly located in the middle and apical thirds of mesial root of first mandibular molars [9]. The present study tried to compare irrigation parameters when conventional irrigation is used alone or in combination with different suction cannulas in mesial roots of human mandibular molars with 2 independent canals and isthmus communications.

In vitro or *ex vivo* studies have provided answers to the antimicrobial and tissue dissolving capacity of hypochlorite [23] the penetration of irrigant solutions in lateral canals [24] or the influence of surfactants in the improvement of irrigation [25]. Although research on irrigation in the presence of isthmuses is limited, Iandolo *et al.* 2021 have shown that heat and/or activation aided conventional irrigation of root canal systems with anatomical complexities such as isthmuses [26]. The present study tried to further understand irrigation parameters in complex anatomies. CFD has been commonly used to better comprehend the key parameters of irrigation in artificial anatomies like regular cones simulating a root canal [27–29]. However, although the use of artificial models provides valuable information, the results may not be extrapolated to a complex clinical situation with anatomical irregularities. In fact, the influence of the simultaneous use of aspiration cannulas with positive pressure irrigation needles was previously analyzed in artificial anatomies with a simulated isthmus [30]. When compared to the current study with real anatomies, higher velocities and a more favorable fluid flow were observed highlighting the overcompensation of artificial models.

Wang *et al.* published the first study in a real anatomy combining the use of micro-Ct and CFD [20]. Instead of a simple anatomy, the current study included a more complex model with an isthmus communication between the root canals using a high-resolution micro-Ct scan.

At the same time, CFD studies have demonstrated that apical root canal preparations to sizes 20 or 25/.06 did not allow the irrigant solution to reach WL, but when increased to 30/.06, a 30G open-ended needle allowed the irrigant to reach WL even at low flow rates. A 31G closed-ended needle also delivered the irrigant to WL when delivered with a high flow rate, but this strategy also led to higher wall shear stress and very importantly developed higher apical pressure [31].

Pereira *et al.* combined an *in vitro* experimentation with CFD and observed that the higher the flow velocity, the higher the shear stress values in the isthmus, correlating the increase in the irrigation velocity with greater biofilm elimination [32].

The present study used an SV needle due to its effectiveness and lack of risk of extrusion previously reported in CFD studies [17, 27, 29], although it also showed ineffective flow in real anatomies with irregularities such as a c-canal resembling an isthmus [20] or artificial isthmuses [32]. However, Thomas *et al* reported in an *in vitro* study that the combination of conventional irrigation and an adjuvant suction cannula (MaC) improved the debridement capacity when a root presented 2 independent canals with an isthmus communication [19]. The current study reproduced this methodology using CFD and confirmed the benefits of combining suction cannulas in one of the root canals while applying positive pressure irrigation in the other in the presence of an isthmus communication. The introduction of suction cannulas generated higher velocities in the coronal and middle third of MB root canal, as expected when using the negative pressure, being the iNP cannula the least effective. The negatives pressures produced by MaC or SURG cannulas directed the flow towards the isthmus up to the entrance of the cannula, increasing the velocity of the irrigant and generating a higher shear stress when the flow first encountered the root canal wall.

The distribution of shear stress is a parameter that has not been studied in depth in endodontics. Although the values of shear stress needed to eliminate biofilm or debris from the walls of the root canal are currently unknown, the implications are relevant. The greater the shear stress generated, the greater the force exerted by the irrigant in the root canal wall. The present study showed how when cannulas such as MaC or SURG (with a larger internal diameter) are placed 7.5 mm from the WL, the shear stress increased notably when compared to smaller internal diameters (iNP) with the highest values located in three different sites (at the exit of the irrigation needle, in the center of the isthmus and at the entrance of the suction cannula). The insertion of a suction cannula coronal to the isthmus seems to help the irrigant delivered in the other root canal to reach the isthmus accelerating the flow and increasing the shear stress in this narrow area. At the same time the use of a SL needle guarantees a low apical pressure, that was very similar for all the simulations, decreasing slightly with the use of the cannulas.

Within the limitations of this study, it can be concluded that the use of adjuvant suction cannulas aids conventional irrigation in roots with 2 independent root canals and isthmus communication by improving irrigant flow, increasing shear stress in the root canal walls and isthmus, and slightly decreasing apical pressure.

Declarations

Conflict of interest The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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