WORLD JOURNAL OF PHARMACEUTICAL RESEARCH
SJIF Impact Factor 8.084
Volume 10, Issue 4, 885-901. Review Article ISSN 2277– 7105

CURRENT CHALLENGES AND STRATEGIES IN THE PREPARATION OF ROOT CANAL SYSTEMS, HIGHLIGHTING THE ROLE OF NITI ROTARY INSTRUMENTS: AN OVERVIEW

Dr. Arvind Jain*[1], Dr. Ashish Saxena[2], Dr. Ajaypratap Singh Parihar[3] Dr. Amit awat[4], Dr. Sandhya Jain[5]

[1]Reader, Department of Conservative Dentistry and Endodontics.

[2]Prof and HOD Department of Pediatric Dentistry.

[3]Prof and HOD Department of Oral Medicine.

[4]Reader, Dept of Oral and Maxillofacial Surgery.

[5]Prof and HOD, Department of Orthodontics.

Article Received on
08 Feb. 2021,

Revised on 01 March 2021,
Accepted on 22 March 2021

DOI: 10.20959/wjpr20214-20147

***Corresponding Author**
Dr. Arvind Jain
Reader, Department of Conservative Dentistry and Endodontics.

ABSTRACT

This review article provides rationale behind using NiTi Rotary instruments for the root canal management overcoming the anatomical road blocks and diagnostic limitations of conventional radiographs and other operative technical difficulties. The article will further delineate the importance of currently used heat treated NiTi alloys and usage of irrigants in cleaning the root canal system using upgraded endodontic files and instrumentation techniques. The article will discuss the significance of achieving the perfect antimicrobial status for the root canal and current ways to attain larger than optimum geometries with wider apical canal using NiTi rotary instruments.

INTRODUCTION

During root canal treatment ultimate target of an Endodontist is the cure and prevention of apical periodontitis. This treatment process involves diseased vital and necrotic dental pulp so as to maintain function and appearance of natural tooth. Successful outcome depends upon a list of factors, the most crucial of which is root canal preparation as it determine the efficacy of subsequent process of debridement, disinfection and obturation of root canal system.[1,2]

Canal preparation is achieved by use of endodontic rotary instruments. Initially stainless steel files were used but the introduction of nickel–titanium (NiTi) alloys in the late 1980s led to

revolutions in endodontics as these files were shown to have substantial amount of benefits over stainless steel (SS) files, especially in relation to the safety of instrumentation.[3]

A meticulous and complete knowledge of tooth and root canal morphology is a prime requirement for successful root canal therapy (Kato & Ohno 2009). In clinical practice, however, dentists frequently encounter anatomically aberrant cases.[4]

Tooth anatomy and root canal morphology maybe quite variable within the norm. Anomalies or deviations in the usual shape and root number in the adult human dentition outside the norm may also occur.[5]

More than 80% of dentists missed extra roots and root curvature buccally and less than 50% said that they would be able to interpret canal morphology. Thus Pre-operative diagnostic radiograph by general dental practitioners for root canal treatment interpretation is variable and difficult.[6]

Root canal preparation has been considered the most important step in endodontic therapy for dentin removal. It is a challenge for even the most experienced endodontist to achieve optimum cleaning and shaping.[7]

Main challenges faced while root canal shaping are

- Detection, centrally accessed approach throughout and instrumentation of canal without transportation, leak or any other aberration.
- Working length should be maintained throughout.
- Selection of optimum preparation sizes and overall geometries that allow adequate disinfection and subsequent obturation.[1,5]

Our review attempts to delineate and report various issues in root canal preparation in current scenario and approaches to overcome that with variable root canal anatomy and diagnostic limitation of conventional low cost radiographs with other technical issues.

For achieving that literature were searched in electronic database from Pubmed, web of science and Scopus for articles pertaining to NiTi rotary instruments, NiTi instruments, root canal and associated literature. After exhaustive list of articles 66 articles were finalized Reviews and concepts were then methodically analyzed and presented. Because of

heterogeneity among the included studies, quantitative synthesis was not performed for most of the parameters.

Anatomical factors and strategies to deal with it

During instrumentation, debridement or obturation of canal the the clinician have to face many challenges due to variable and complex anatomy of canal(s). In C-shaped root canals there is presence of broad, fan-shaped connection from the coronal to the apical third of the canal. The canal(s) shows deviation in shape from the coronal aspect of the root. Such as a continuous C-shaped canal would change to a semicolon shape in the midroot and then may become continuous C-shape in the apical third of the root or vice versa.[8]

In the apical region of C-shaped canals accessory and lateral canals, inter-canal communications and apical delta is found to be in a prevalence of 11-41%.[9]

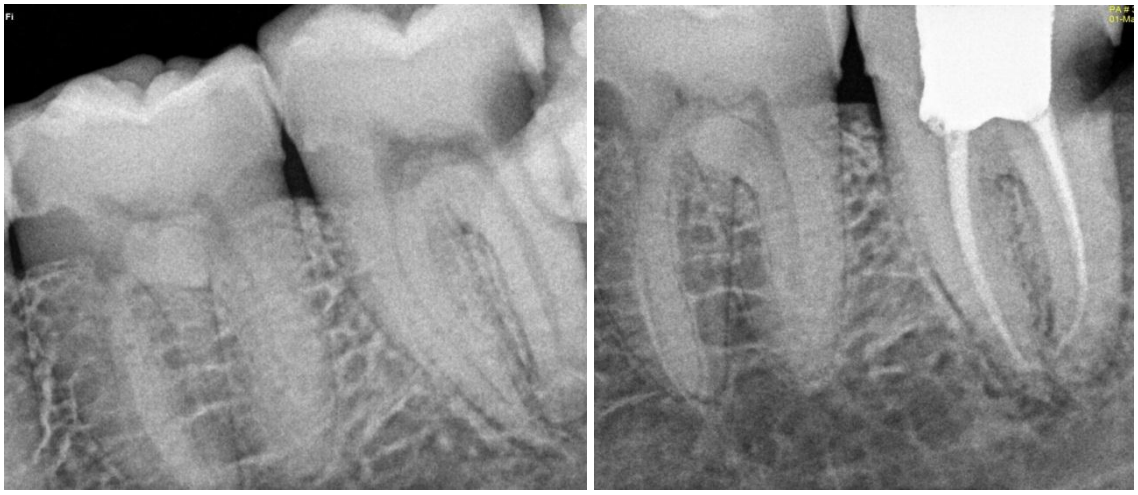
Mean for minimum width was 0.58 Â± 0.21 mm for the lingual canal wall and that of buccal wall was 0.96 Â± 0.26 mm. This indicated that thinner lingual walls of C-shaped canals are at higher risk of root perforation during shaping and post canal preparation procedures. However both buccal and lingual canal walls were found to be frequently narrower at mesial locations.[10]

Preoperative assessment of the root canal morphology mostly clinically and radiologically is thus necessary so that the complexity, the degree of curvature and radius of the root canals are determined to maximum possible extent. All aforementioned assessment done prior to any instrumentation will thus reduce the occurrence of any procedural errors and the excess removal of tooth structure from the inner curvature, resulting in stripping or zip formation.[11]

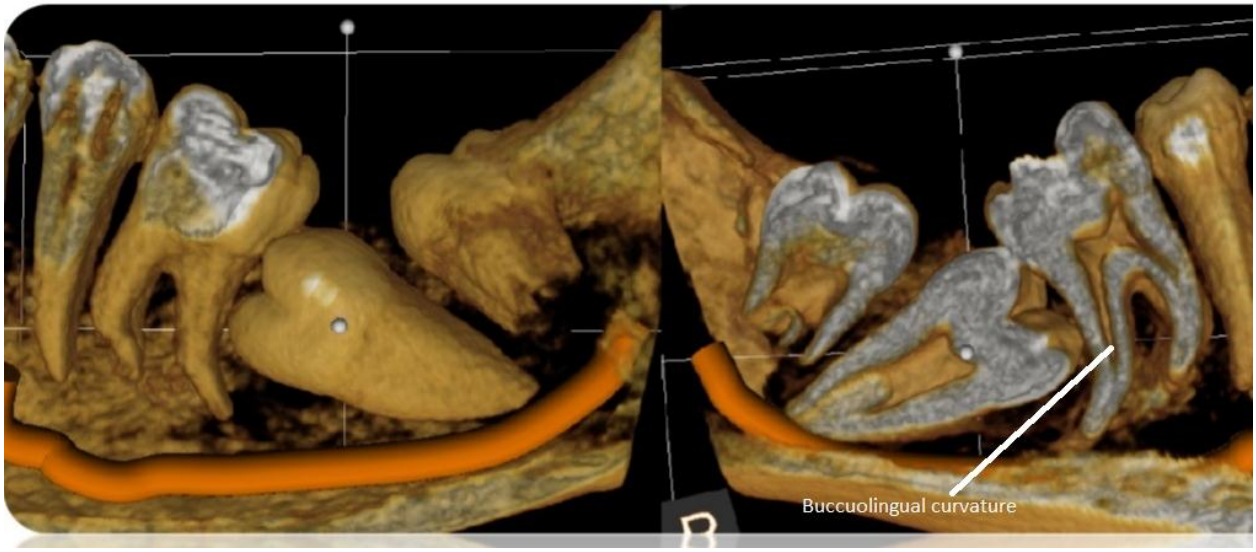
Radiographic images are two-dimensional image of a three-dimensional object, as a result there is superimposition of adjacent anatomic structures (Shown in image 1 A and B) and buccolingual curvature may not be visible.[12] Geometrical alterations was found with distortion degree of the anatomic structures which ranges from 3.4% for the periapical radiograph to more than 14% for OPT (orthopantomography).[13]

CBCT delineate root canal anatomical forms to a far greater extent as compared to radiographs including buccolingual curvatures. **(Shown in Image 2)** CBCT imaging is very useful to interpret buccolingual information in detailed manner, to demarcate and define the limit and extent of root resorption, and to delineate orientation of long axis of unerupted

teeth, including root apex location.[12] The radius of root curvature can also be determined through CBCT using Schneider's, Cunningham's and Senia's or Weine's method.[11] If the angle is less than 5°, the canal is straight; if the angle is 5-20°, the canal is moderately curved; and if the angle is greater than 20°, the canal is classified as a severely curved canal.[14,15]



RVG-1A and B showing superinposition of root canal.



CBCT image showing Buccuolingual Curvature.

Iatrogenic risk during root canal preparation and strategies to overcome

It is imperative to select the correct instruments and instrumentation techniques as the final result of entire endodontic treatment in curved canals depends largely on the flexibility of the instruments used, diameter of the instrument, and technique of the instrumentation.[16]

With modern technologies in the field of metallurgy, manufacturers have tried hard to improve the instruments (easier, faster and better root canal shaping, greater resistance to fracture), for example those made of M wire (Dentsply Tulsa Dental Specialties, Tulsa, OK, USA) or control memory wire (CM) (DS Dental, Johnson City, TN, USA), which are also incorporated with several design features. Along with these recent advancements endodontic motors too have undergone enhancement regarding torque control and kinematics that are adjustable in several directions.[17]

There can be lot of procedural iatrogenic errors while preparation of curved root canals, such as zips, perforations, decentralized root canals, apical foramen transport which are potential risk factors which may lead to root canal treatment failure.[18,19]

Nickel titanium's super elastic property is a boom allows more centered canal preparations with less transportation and a decreased incidence of canal aberrations. But main issue with NiTi alloy instrument is separation of instrument within the canal. The rate of separation of nickel titanium is 30-60% and breakage rate 9.4 %.[20,21] It is found that as the radius of curvature of canal increases, the frequency for instrument separation also increases.[22]

A canal with 50° curvature gives rise to stress of about 700–800 MPa on the outermost part of the instrument, whereas ultimate tensile strength of NiTi is 1400 MPa.[23]

Fracture of instruments occurs commonly within the apical one-third where torsional and flexural stresses are highest. A flexible file has more cyclic fatigue resistance (CFR) but less Torsional resistance (TR) and enables a smoother preparation in curved canals without being deformed. Contrary to this a rigid file would be good in torsion than in flexion and performs better in narrow, constricted canals. Hence it is clear that cyclic and torsional properties are in inverse relationship with each other.[24] Hence flexible fie are preferred for curved canal and K-file (rigid) for straight canals.

Treatment of nickel-titanium instruments

Heat treatment or thermal processing is one of the most fundamental approaches toward adjusting the transition temperature in NiTi alloy, which affects the fatigue resistance of NiTi endodontic files. The recently introduced NiTi instruments are made from controlled memory wire, M-Wire (Dentsply Tulsa Dental Specialties, Tulsa, OK), or R-phase wire which

represent the next generation of NiTi alloys with improved flexibility and fatigue resistance and the resistance to cyclic fatigue and torsion.[25]

Endodontic files alloy properties

Recently it is found that the use of single NiTi files is much better as it decreases the preparation time, being cost-effective also and reduces the risk of cross-contamination.[26] The research studies found for the ProTaper Next, ProTaper Gold, WaveOne Gold, Mtwo, BioRaCe and Reciproc files in the analysis of transportation and centering ability after the preparation of curved root canals concludes that they preserved the shape of root canals.[27,28,29,30]

EdgeTaper Platinum showed significantly greater fatigue resistance than ProTaper Gold. ProTaper Universal and EdgeTaper each demonstrated significantly greater fatigue resistance than ProTaper Gold vs EdgeTaper Platinum; and Vortex Blue vs Edge Sequel Sapphire system in 1 size pairing. In brief the heat-treated files demonstrated greater cyclic fatigue resistance than the non-heat-treated files.[31]

ProTaper (PT; Dentsply Maillefer, Ballaigues, Switzerland) system removed a significantly higher amount of dentin than Revo-S (RS; Micro-Mega, Besancon Cedex, France), Twisted file (TF; SybronEndo, Amersfoort, The Netherlands) ProFile GT Series X (GTX; Dentsply, Tulsa Dental Specialties, Tulsa, OK) and ProTaper (PT; Dentsply Maillefer, Ballaigues, Switzerland). It was found that Twisted File maintained the existing canal curvature showing least amount of canal transportation as well as the highest mean centering ratio.[32]

The Pow-R system presented the lowest mean apical displacement value compared to Quantec, Pro-file Maillefer, Pro-file Tulsa and Stainless steel Hand files. Stainless steel hand files showed maximum apical displacement.[33]

Endodontic motors in root canal instrumentation

The main problem with the NiTi rotary instrumentation technique is fracture of instrument within the canal. During process of shaping rotary instruments might lock and/or screw into canals and, consequently are subjected to high levels of stress. This may frequently cause instrument separation or deformation. When there is use of high-torque motor the applied forces are usually very high and as a result the instrument-fracture limit is usually exceeded, thus increasing the risk of intracanal failure. A possible solution of this problem is to use a

low-torque endodontic motor, which operates below the maximum permissible torque limit of each and every rotary instrument. During clinical instrumentation of root canals, if a torque-controlled motor reaches the limit of instrument-specific torque, the motor stops momentarily and/or starts rotating counter-clockwise (auto-reverse function) to disengage the locked instrument. These safety mechanisms were developed to reduce the risk of instrument fracture.[34,35]

Reciprocation

It has been shown that instruments subjected to reciprocation have increased resistance to fatigue and longer usual life when combined with instruments utilized in continuous rotation motion. The reciprocating system uses single-file instrumentation technique which can shape and clean the canal in a shorter period and together with the lesser amount of antimicrobial agent.[36] The instruments moved by reciprocating movement reached significantly higher numbers of cycles before fracture (mean, 1787.78 cycles) when compared with instruments moved by continuous rotary (mean, 816.39 cycles).[37] Contemporary instrument design combined with reciprocating action promises single file root canal preparation which is less expensive than multiple file NiTi systems. The reciprocating movement occurs in an anticlockwise cutting movement purported to be 130 degrees, followed by a clockwise releasing movement of 50 degrees. This means that each instrument takes three rotations to complete a full 360 degree rotation and thus the elastic limit of the instrument is not exceeded.[38]

Irrigants

A perfect and a model irrigant is one which removes the smear layer completely, lubricate the root canal properly, efficiently kills the bacteria, produce minimal or no inflammatory response in the surrounding tissues and simultaneously doesn't causes any damage to dentin structure. Brenda P F A Gomes et al.[39] quoted that In Endodontic dentistry Chlorhexidine (CHX) has been used not only as an irrigating substance but also used for intracanal medicament since it carries a wide range of antimicrobial activity, substantivity (residual antimicrobial activity), lower cytotoxicity than NaOCl whilst demonstrating efficient clinical performance, lubricating properties, rheological action (present in the gel presentation, keeping the debris in suspension); it inhibits metalloproteinase, is chemically stable, does not stain cloths, it is odorless, water soluble, among other properties. Along with instrumentation, lubrication is required to facilitate the mechanical action of hand/rotary files and to assist

emulsify and suspend the debris produced. Aqueous irrigation solutions such as sodium hypochlorite and ethylenediaminetetraacetic acid (EDTA) should be regarded as lubricants, but paste-type substances are marketed specifically for this purpose.[40] It is recommended by mostly all manufacturers of nickel-titanium instruments to use EDTA or NaOCl as a lubricant during rotary root canal preparation. Additionally, a final irrigation of the root canal with 15-17% EDTA solutions to dissolve the smear layer is recommended.[41] Sodium hypochlorite (NaOCl) is suggested as an endodontic irrigant in sight of its broad antimicrobial and tissue dissolution capacities. To enhance its penetration into inaccessible areas of root canals and to enhance its overall effect, the addition of surface-active agents has been suggested.[42] QMix is a root canal irrigation mixture of ethylenediaminetetraacetic acid (EDTA), chlorhexidine (CHX) and surfactant. This mixture can remove the smear layer efficiently, and it possesses strong antibacterial effect and good biocompatibility with minimal cytotoxicity.[43]

Determination and Maintenance of Working Lengths

During root canal preparation debris that may also contain bacteria, necrotic pulp tissue and dentine can be introduced into the periapical tissues.[44] If the working length is underestimated, tissue residues and/or bacteria will remain within the non-instrumented areas of the root canal system. Else in another case for example, if the working length is determined beyond the apical boundaries, vital and/or infected material will be transported into the adjacent periapical tissues. An erroneously determined working length will most likely compromise the result of an endodontic treatment, because it will cause shaping and filling procedures that are inaccurate. This can cause periapical tissue inflammation and/or infection.[45,46] It is possible that certain factors can be controlled by the operators such as selection of endodontic file systems and technique of root canal preparation but virulence of the microorganisms extruded beyond apex is almost impossible to control.[47,48] However there were no significant differences between the results of digital radiography, conventional film and self-developing film methods in working length determination, the clinician can choose any of these methods according to the working conditions without being concerned about losing the accuracy.[49] Measuring the location of the apical constriction using the four apex locators was more accurate than radiographs and would reduce the risk of instrumenting and filling beyond the apical foramen.[50] The precision of electronic working length measurement depends on the device used and the type of irrigation and is not influenced by the status of the pulp tissue.[51]

Recently 3D Endo software has been launched which is mostly dedicated for complicated endodontic cases in the clinical situation. 3D Endo is the first CBCT software that allows endodontic treatment to be pre-planned and optimised using imaging data from Orthophos X-ray units, enabling the user to isolate the tooth being treated and locate the orifice and apex of the canals.[52] The 3D Endo Software allows the clinicians to visualize endo files within the root canal. The file position and bending is defined from the canal mid-line identified by the user without any clinical interpretation of the specific tooth anatomy. But the mechanical and geometrical properties of the root canal and the file are not taken into account by the 3D Endo Software. Therefore the 3D Endo Software cannot predict file separation nor automatically indicate risky canal curvatures.[53] On Comparing the accuracy of the 3D Endo software, conventional CBCT software, Romexis Viewer, and the EAL E-Pex Pro for determining the working length the EAL E-Pex Pro was the best accurate modality among the experimental ones.[54]

Apical extrusion debris

Recent researches have shown that reciprocating instrumentation techniques seem to significantly increase the quantity of debris extruded beyond the apex and, consequently, the danger of postoperative pain.

The study conducted to evaluate ex vivo the maintenance of the apical limit during instrumentation with the Root ZX (J Morita, Tokyo, Japan) and VDW Gold (VDW GbmH, Munich, Germany) hybrid devices in rotary and reciprocating modes. It was found that both are efficient in the maintenance of the apical limit when used until the apical foramen; however, such reliability was compromised when -1.0 mm from the apical limit was established.[55]

The least amount of apically extruded debris after canal shaping with WaveOne Gold than the RECIPROC Blue, and HyFlex EDM One file. Difference between WaveOne Gold and HyFlex EDM suggests that file design and motion kinematics affect the quantity of debris extrusion.[56] WaveOne gold in reverse reciprocation was associated with a considerably lower amount of apical extrusion of debris than ProTaper next rotary files in forward reciprocation and continuous rotation. Reciprocating instrumentation technique was associated with a less amount of debris extrusion compared to continuous rotation.[57]

Optimal apical preparation size (APS)

Root canals should be shaped to larger sizes than normally recommended. Instrument designs, alloy properties, and canal curvature are important factors that determine the feasibility of greater apical enlargement in narrow canals.[58,59] The presence of a periradicular inflammatory reaction determines the presence of a larger diameter compared to cases without periapical lesions.[60] In root canals of the palatal roots apical constriction was identified in 38% of the roots and also the main foramen did not coincide with the root apex in 95% of the cases.[61] Usman et al. demonstrated that the quantity of irrigant delivered increased with numbers of recapitulations. It suggests that canal diameter and curvature play an important role in irrigation efficacy along with the needle types of syringes used for irrigation.[62] The hydrodynamic and ultrasonic irrigation techniques were significantly ($P < .001$) more efficient as compared with syringe irrigation in both the straight and curved root canals. Ultrasonic irrigation demonstrated a higher efficiency in the straight root canals ($P < .01$), whereas hydrodynamic irrigation was more efficient in the curved canals ($P < .01$).[63]

Age-dependent root canal instrumentation techniques

With advancing age changes occur in the morphology of the root canal system and the structural features of dentin. Individuals less than 20 years of age only scraping instruments can be used.[64] For individuals who are 20 to 40 years old regular nickel-titanium (NiTi) rotary systems can be used to shape the canal up to an apical diameter size of #30–#35.[65] For individuals who are 40 years old or more after the use of manual stainless-steel K-files (#06, #08, and #10), a NiTi system for the glide path can be used Afterward, widening of the canal apical diameter up to size #30 or #35 is preferably done with NiTi instruments, which create less loading on dentin.[64,66] To summarize antimicrobial efficacy in root canal preparation is very significant and successfully achieved by proper working length and apical width estimation.

CONCLUSION

During routine conventional practice of root canal therapy with unchangeable canal anatomy where every case is a new one this blind procedure with associated risk factor no doubt is a challenge for even a well experienced operator.

The introduction of NiTi rotary instruments leads to a boom in the field of Endodontics. With careful preoperative assessment of canal and associated pathologies the further operative procedure involving instrumentation using recent advance techniques and process leads to a

very significant improvement in result output with negligible chances of root canal treatment failure. Super flexibility and shape memory properties of improved NiTi instruments with advanced torque controlled devices and adjuncts such as lubricants and mechanized antimicrobial canal preparation leads to a wider apex and well prepared canal for obturation with limited treatment failure. Also thus nickel-titanium (NiTi) files are broadly used to shape the root canals owing to their increased flexibility, rapid and centered canal preparation, safer preparation of curved canals, improved cutting efficiency, and improved treatment outcome.

REFERENCES

1. Peters OA. Current challenges and concepts in the preparation of root canal systems: a review. J Endod, Aug, 2004; 30(8): 559-67. doi: 10.1097/01.don.0000129039.59003.9d. PMID: 15273636.
2. Tomson RM, Polycarpou N, Tomson PL. Contemporary obturation of the root canal system. Br Dent J., Mar, 2014; 216(6): 315-22. doi: 10.1038/sj.bdj.2014.205. PMID: 24651337.
3. Walia HM, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of Nitinol root canal files. J Endod, 1988; 14(7): 346–51. [PubMed] [Google Scholar]
4. Kato A, Ohno N. Construction of three-dimensional tooth model by micro-computed tomography and application for data sharing. Clinical Oral Investigations, 2009; 13: 43–6. [PubMed] [Google Scholar]
5. DDS, I., Rotstein, &. (2019). Ingle's Endodontics. PMPH USA.
6. Sherwood IA. Pre-operative diagnostic radiograph interpretation by general dental practitioners for root canal treatment. Dentomaxillofac Radiol, 2012; 41(1): 43-54. doi:10.1259/dmfr/26466415
7. Michael H, Peters OA, Dummer PMH. Mechanical preparation of root canals: shaping goals, techniques andmeans. Endodontic Topics, 2005; 10: 30-76
8. Melton DC, Krell KV, Fuller MW. Anatomical and histological features of C-shaped canals in mandibular second molars. J Endod, 1991; 17: 384–8. [PubMed] [Google Scholar]
9. Morphometric study of the apical anatomy of C-shaped root canal systems in mandibular second molars.Cheung GS, Yang J, Fan BIntEndod J., Apr, 2007; 40(4): 239-46. [PubMed]

10. Cross-sectional morphology and minimum canal wall widths in C-shaped roots of mandibular molars.Chai WL, Thong YLJ Endod, Jul, 2004; 30(7): 509-12.
11. Balani P, Niazi F, Rashid H. A brief review of the methods used to determine the curvature of root canals J. Res Dent, 2015; 3: 57-63.
12. Becker A, Chaushu S, Casap-Caspi N. Cone-beam computed tomography and the orthosurgical management of impacted teeth. J Am Dent Assoc, Oct, 2010; 141(3): 14S-8S. doi: 10.14219/jada.archive.2010.0360. PMID: 20884935.
13. Lo Giudice R, Nicita F, Puleio F, et al. Accuracy of Periapical Radiography and CBCT in Endodontic Evaluation. *Int J Dent.*, 2018; 2018: 2514243. Published 2018 Oct 16. doi:10.1155/2018/2514243
14. Zhu Y, Gu Y, Du R, Li C. Reliability of two methods on measuringroot canal curvature. Int Chin J Dent., 2003; 3: 118‑21.
15. Bürklein S, Schäfer E. Critical evaluation of root canaltransportation by instrumentation. Endod Topics, 2013; 29: 110‑24.
16. Sakkir N, Thaha KA, Nair MG, Jospeh S, Christalin R.Management of dilacerated and S‑ shaped root canals‑Anendodontic challenge. J ClinDiagn Res., 2014; 8: ZD22‑4
17. Çapar ID, Arslan H. A review of instrumentation kinematics of engine-driven nickel-titanium instruments. IntEndod J., Feb, 2016; 49(2): 119-35. doi: 10.1111/iej.12432. Epub 2015 Feb 18. PMID: 25630977.
18. de Alencar AH, Dummer PM, Oliveira HC, Pécora JD, Estrela C. Procedural errors during root canal preparation using rotary NiTiinstruments detected by periapical radiography and cone beam computed tomography. Braz Dent J., 2010; 21(6): 543-9. [http://dx.doi.org/10.1590/S0103-64402010000600011] [PMID: 21271046]
19. Estrela C, Holland R, Estrela CR, Alencar AH, Sousa-Neto MD, Pécora JD. Characterization of successful root canal treatment. Braz Dent J., 2014; 25(1): 3-11. [http://dx.doi.org/10.1590/0103-6440201302356] [PMID: 24789284]
20. Szep S, Gerhardt T, Leitzbach C, et al. Preparation of severely curved simulated root canals using engine-driven rotary andconventional hand instruments. Clin Oral Investig, 2001; 5(1): 17-25.
21. Baumann MA, Roth A. Effect of experience on quality of canal preparation with rotary nickel-titanium files. Oral Surg Oral MedOral Pathol Oral RadiolEndod, 1999; 88(6): 714-718.

22. Martin B, Zelada G, Varela P, Babillio JG, Magan F, Ahn S, et al. Factors influencing the fracture of niTi rotary instruments. IntEndod J., 2003; 36: 1394–8. [Google Scholar] [Ref list]
23. Influence of cross-sectional design and dimension on mechanical behavior of nickel-titanium instruments under torsion and bending: a numerical analysis. Zhang EW, Cheung GS, Zheng YFJ Endod, Aug, 2010; 36(8): 1394-8.
24. Comparison of torsional stiffness of nickel-titanium rotary files with different geometric characteristics.Baek SH, Lee CJ, Versluis A, Kim BM, Lee W, Kim HCJ Endod, Sep, 2011; 37(9): 1283-6.[PubMed]
25. Shen Y, Zhou HM, Zheng YF, Peng B, Haapasalo M. Current challenges and concepts of the thermomechanical treatment ofnickel-titanium instruments.
26. Yared G. Canal preparation using only one Ni-Ti rotary instrument: preliminary observations. International Endodontic Journal, 2008; 41(4): 339–344. doi: 10.1111/j.1365-2591.2007.01351.x. [PubMed] [CrossRef] [Google Scholar]
27. Gagliardi J, Versiani MA, de Sousa-Neto MD, Plazas-Garzon A, Basrani B. Evaluation of the shaping characteristics of proTaper gold, proTaper NEXT, and proTaper universal in curved canals. J Endod, 2015; 41(10): 1718-24. [http://dx.doi.org/10.1016/j.joen.2015.07.009] [PMID: 26321062]
28. Yang G, Yuan G, Yun X, Zhou X, Liu B, Wu H. Effects of two nickel-titanium instrument systems, Mtwo versus ProTaper universal, on rootcanal geometry assessed by micro-computed tomography. J Endod 2011; 37(10): 1412-6.[http://dx.doi.org/10.1016/j.joen.2011.06.024] [PMID: 21924193]
29. Bürklein S, Mathey D, Schäfer E. Shaping ability of ProTaper NEXT and BT-RaCe nickel-titanium instruments in severely curved rootcanals. IntEndod J., 2015; 48(8): 774-81. [http://dx.doi.org/10.1111/iej.12375] [PMID: 25156248]
30. García M, Duran-Sindreu F, Mercadé M, Bueno R, Roig M. A comparison of apical transportation between ProFile and RaCe rotaryinstruments. J Endod, 2012; 38(7): 990-2. [http://dx.doi.org/10.1016/j.joen.2012.03.022] [PMID: 22703667]
31. Weyh DJ, Ray JJ. Cyclic fatigue resistance and metallurgic comparison of rotary endodontic file systems. Gen Dent, Jan-Feb, 2020; 68(1): 36-39. PMID: 31859660.
32. Hashem AA, Ghoneim AG, Lutfy RA, Foda MY, Omar GA. Geometric analysis of root canals prepared by four rotary NiTi shaping systems. J Endod. 2012 Jul;38(7):996-1000. doi: 10.1016/j.joen.2012.03.018. Epub, May 11, 2012. PMID: 22703669.

33. Vanni JR, Albuquerque DS, Reiss C, Baratto Filho F, Limongi O, Della Bona A. Apical displacement produced by rotary nickel-titanium instruments and stainless steel files. J Appl Oral Sci., Mar, 2004; 12(1): 51-5. doi: 10.1590/s1678-77572004000100010. PMID: 21365152.
34. Gambarini G. Advantages and disadvantages of new torque-controlled endodontic motors and low-torque NiTi rotary instrumentation. Aust Endod J., Dec, 2001; 27(3): 99-104. doi: 10.1111/j.1747-4477.2001.tb00466.x. PMID: 12360669.
35. Sattapan B, Palamara JE, Messer HH. Torque during canal instrumentation using rotary nickel-titanium files. J Endod, Mar, 2000; 26(3): 156-60. doi: 10.1097/00004770-200003000-00007. PMID: 11199710.
36. Siddique R, Nivedhitha MS. Effectiveness of rotary and reciprocating systems on microbial reduction: A systematic review. *J Conserv Dent.,* 2019; 22(2): 114-122. doi:10.4103/JCD.JCD_523_18
37. Gavini G, Caldeira CL, Akisue E, Candeiro GT, Kawakami DA. Resistance to flexural fatigue of Reciproc R25 files under continuous rotation and reciprocating movement. J Endod, May, 2012; 38(5): 684-7. doi: 10.1016/j.joen.2011.12.033. Epub 2012 Jan 24. PMID: 22515903.
38. Prichard, J. Rotation or reciprocation: a contemporary look at NiTi instruments?. *Br Dent J*., 2012; 212: 345–346. https://doi.org/10.1038/sj.bdj.2012.268
39. Gomes BP, Vianna ME, Zaia AA, Almeida JF, Souza-Filho FJ, Ferraz CC. Chlorhexidine in endodontics. Braz Dent J., 2013; 24(2): 89-102. doi: 10.1590/0103-6440201302188. PMID: 23780357.
40. Chandler N, Chellappa D. Lubrication during root canal treatment. Aust Endod J., Apr, 2019; 45(1): 106-110. doi: 10.1111/aej.12282. Epub 2018 Aug 13. PMID: 30105836.
41. Hülsmann M, Heckendorff M, Lennon A. Chelating agents in root canal treatment: mode of action and indications for their use. Int Endod J., Dec, 2003; 36(12): 810-30. doi: 10.1111/j.1365-2591.2003.00754.x. PMID: 14641420.
42. Rossi-Fedele G, Prichard JW, Steier L, de Figueiredo JA. The effect of surface tension reduction on the clinical performance of sodium hypochlorite in endodontics. Int Endod J., Jun, 2013; 46(6): 492-8. doi: 10.1111/iej.12022. Epub 2012 Nov 27. PMID: 23186034.
43. Jiayi W, Ruijie H. [Research progress on QMix properties in root canal irrigation]. Hua Xi Kou Qiang Yi Xue Za Zhi, Oct 1, 2017; 35(5): 543-548. Chinese. doi: 10.7518/hxkq.2017.05.019. PMID: 29188654; PMCID: PMC7030402.

44. Kuştarci A, Akpinar KE, Er K. Apical extrusion of intracanal debris and irrigant following use of various instrumentation techniques. Oral Surg Oral Med Oral Pathol Oral Radiol Endod, 2008; 105: 257–62. 10.1016/j.tripleo.2007.06.028 [PubMed] [CrossRef] [Google Scholar]
45. Sjögren U, Hagglund B, Sundqvist G, Wing K. Factors affecting the long-term results of endodontic treatment. *J. Endod,* 1990; 16: 498–504. doi: 10.1016/S0099-2399(07)80180-4. [PubMed] [CrossRef] [Google Scholar]
46. Farzaneh M, Abitbol S, Lawrence HP, Friedman S. Treatment outcome in endodontics-the Toronto Study. Phase II: Initial treatment. *J. Endod,* 2004; 30: 302–309. doi: 10.1097/00004770-200405000-00002. [PubMed] [CrossRef] [Google Scholar]
47. Tanalp J, Güngör T. Apical extrusion of debris: a literature review of an inherent occurrence during root canal treatment. *Int Endod J.*, 2014; 47: 211–21. 10.1111/iej.12137 [PubMed] [CrossRef] [Google Scholar]
48. Tanalp J, Kaptan F, Sert S, et al. . Quantitative evaluation of the amount of apically extruded debris using 3 different rotary instrumentation systems. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*, 2006; 101: 250–7. 10.1016/j.tripleo.2005.03.002 [PubMed] [CrossRef] [Google Scholar]
49. Raees Sameye M, Mohammad Bahalkeh A, Izadi A, Jafaryan A. Comparison of Digital Radiography, Conventional Film and Self-Developing Film for Working Length Determination. Iran Endod J., 2018; 13(3): 381-384. doi: 10.22037/iej.v13i3.19355. PMID: 30083210; PMCID: PMC6064012.
50. Vieyra JP, Acosta J. Comparison of working length determination with radiographs and four electronic apex locators. Int Endod J., Jun, 2011; 44(6): 510-8. doi: 10.1111/j.1365-2591.2011.01855.x. Epub 2011 Feb 10. PMID: 21306402.
51. George R. Precision of multi-frequency electronic apex locators. Evid Based Dent, Sep, 2016; 17(3): 86-87. doi: 10.1038/sj.ebd.6401190. PMID: 27767118.
52. Endodontic software for the 3D imaging era. *Br Dent J.*, 2018; 224: 982. https://doi.org/10.1038/sj.bdj.2018.514
53. 3D Endo_DFU_EN (dentsplysirona.com)
54. Nguyen PN, Pham KV. Endodontic length measurements using different modalities: An in vitro study. J Int Soc Prevent Communit Dent, 2020; 10: 752-8.
55. Vasconcelos BC, Frota LM, Souza Tde A, Bernardes RA, Duarte MA. Evaluation of the maintenance of the apical limit during instrumentation with hybrid equipment in rotary

and reciprocating modes. J Endod, May, 2015; 41(5): 682-5. doi: 10.1016/j.joen.2014.11.029. Epub 2015 Jan 13. PMID: 25595465.

56. Elashiry MM, Saber SE, Elashry SH. Apical extrusion of debris after canal shaping with three single-file systems. Niger J Clin Pract, Jan, 2020; 23(1): 79-83. doi: 10.4103/njcp.njcp_319_19. PMID: 31929211.
57. Haridas K, Hariharan M, Singh P, Varughese A, Ravi AB, Varma KR. Effect of Instrumentation Techniques and Kinematics on Apical Extrusion of Debris: An *In Vitro* Study. J Contemp Dent Pract, Sep 1, 2019; 20(9): 1067-1070. PMID: 31797831.
58. Weiger R, Bartha T, Kalwitzki M, Löst C. A clinical method to determine the optimal apical preparation size. Part I. Oral Surg Oral Med Oral Pathol Oral Radiol Endod, Nov, 2006; 102(5): 686-91. doi: 10.1016/j.tripleo.2005.10.058. Epub 2006 Jul 11. PMID: 17052648.
59. Tan BT, Messer HH. The quality of apical canal preparation using hand and rotary instruments with specific criteria for enlargement based on initial apical file size. J Endod, Sep, 2002; 28(9): 658-64. doi: 10.1097/00004770-200209000-00008. PMID: 12236311.
60. Gesi A, Mareschi P, Doldo T, Ferrari M. Apical Dimension of Root Canal Clinically Assessed with and without Periapical Lesions. Int J Dent., 2014; 2014: 374971. doi: 10.1155/2014/374971. Epub 2014 Jun 24. PMID: 25050122; PMCID: PMC4094701.
61. Marceliano-Alves M, Alves FR, Mendes Dde M, Provenzano JC. Micro-Computed Tomography Analysis of the Root Canal Morphology of Palatal Roots of Maxillary First Molars. J Endod, Feb, 2016; 42(2): 280-3. doi: 10.1016/j.joen.2015.10.016. Epub 2015 Nov 26. PMID: 26631299.
62. Usman N, Baumgartner JC, Marshall JG. Influence of instrument size on root canal debridement. J Endodon, 2004; 30: 110–2.
63. Amato M, Vanoni-Heineken I, Hecker H, Weiger R. Curved versus straight root canals: the benefit of activated irrigation techniques on dentin debris removal. Oral Surg Oral Med Oral Pathol Oral Radiol Endod, Apr, 2011; 111(4): 529-34. doi: 10.1016/j.tripleo.2010.11.002. PMID: 21310632.
64. Solomonov M, Kim HC, Hadad A, Levy DH, Ben Itzhak J, Levinson O, Azizi H. Age-dependent root canal instrumentation techniques: a comprehensive narrative review. Restor Dent Endod, Mar 4, 2020; 45(2): e21. doi: 10.5395/rde.2020.45.e21. PMID: 32483538; PMCID: PMC7239687.

65. Arvaniti IS, Khabbaz MG. Influence of root canal taper on its cleanliness: a scanning electron microscopic study. *J Endod.*, 2011; 37: 871–874. [PubMed] [Google Scholar]
66. Kim HC, Lee MH, Yum J, Versluis A, Lee CJ, Kim BM. Potential relationship between design of nickel-titanium rotary instruments and vertical root fracture. *J Endod.*, 2010; 36: 1195–1199. [PubMed] [Google Scholar]