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Mechanical preparation of root canals: shaping goals, techniques and means

MICHAEL HÜLSMANN, OVE A. PETERS & PAUL M.H. DUMMER

Preparation of root canal systems includes both enlargement and shaping of the complex endodontic space together with its disinfection. A variety of instruments and techniques have been developed and described for this critical stage of root canal treatment. Although many reports on root canal preparation can be found in the literature, definitive scientific evidence on the quality and clinical appropriateness of different instruments and techniques remains elusive. To a large extent this is because of methodological problems, making comparisons among different investigations difficult if not impossible. The first section of this paper discusses the main problems with the methodology of research relating to root canal preparation while the remaining section critically reviews current endodontic instruments and shaping techniques.

Introduction

Preparation of the root canal system is recognized as being one of the most important stages in root canal treatment (1, 2). It includes the removal of vital and necrotic tissues from the root canal system, along with infected root dentine and, in cases of retreatment, the removal of metallic and non-metallic obstacles. It aims to prepare the canal space to facilitate disinfection by irrigants and medicaments. Thus, canal preparation is the essential phase that eliminates infection. Prevention of reinfection is then achieved through the provision of a fluid-tight root canal filling and a coronal restoration. Although mechanical preparation and chemical disinfection cannot be considered separately and are commonly referred to as chemomechanical or biomechanical preparation the following review is intended to focus on the mechanical aspects of canal preparation cavity. Chemical disinfection by means of irrigation and medication will be reviewed separately in this issue.

History of root canal preparation

Although Fauchard (3), one of the founders of modern dentistry described instruments for trepanation of teeth, preparation of root canals and cauterization of pulps in his book 'Le chirurgien dentiste', no systematic description of preparation of the root canal system could be found in the literature at that time.

In a survey of endodontic instrumentation up to 1800, Lilley (4) concluded, that at the end of the 18th century ' . . . only primitive hand instruments and excavators, some iron cauter instruments and only very few thin and flexible instruments for endodontic treatment had been available'. Indeed, Edward Maynard has been credited with the development of the first endodontic hand instruments. Notching a round wire (in the beginning watch springs, later piano wires) he created small needles for extirpation of pulp tissue (5, 6). In 1852 Arthur used small files for root canal enlargement (6–9). Textbooks in the middle of the 19th century recommended that root canals should be enlarged with broaches: 'But the best method of forming these canals, is with a three- or four-sided broach, tapering to a sharp point, and its inclination corresponding as far as possible, with that of the fang. This instrument is employed to enlarge the canal, and give it a regular shape' (10). In 1885 the Gates Glidden drill and in 1915 the K-file were introduced. Although standardization of instruments had been proposed in

1929 by Trebitsch and again by Ingle in 1958, ISO specifications for endodontic instruments were not published before 1974 (10).

The first description of the use of rotary devices seems to have been by Oltramare (11). He reported the use of fine needles with a rectangular cross-section, which could be mounted into a dental handpiece. These needles were passively introduced into the root canal to the apical foramen and then the rotation started. He claimed that usually the pulp stump was removed immediately from the root canal and advocated the use of only thin needles in curved root canals to avoid instrument fractures. In 1889 William H. Rollins developed the first endodontic handpiece for automated root canal preparation. He used specially designed needles, which were mounted into a dental handpiece with a 360° rotation. To avoid instrument fractures rotational speed was limited to 100 r.p.m. (12). In the following years a variety of rotary systems were developed and marketed using similar principles (Fig. 1).

In 1928 the 'Cursor filing contra-angle' was developed by the Austrian company W&H (Bürmoos, Austria). This handpiece created a combined rotational and vertical motion of the file (Fig. 2). Finally, endodontic handpieces became popular in Europe with the marketing of the Racer-handpiece (W&H) in 1958 (Fig. 3) and the Giromatic (MicroMega, Besançon, France) in 1964. The Racer handpiece worked with a vertical motion, the Giromatic with a reciprocal 90° rotation. Further endodontic handpieces such as the Endolift (Kerr, Karlsruhe, Germany) with a combined vertical and 90° rotational motion and similar devices were marketed during this period of conventional endodontic handpieces. All these devices worked with limited, if any, rotation and/or a rigid up and down motion of the instrument, which were all made from stainless steel. The dentist could only influence the rotational speed of the handpiece and the vertical amplitude of the file movement by moving the handpiece (10, 13).

A period of modified endodontic handpieces began with the introduction of the Canal Finder System (now distributed by S.E.T., Gröbenzell, Germany) by Levy (14). The Canal Finder was the first endodontic handpiece with a partially flexible motion. The amplitude of the vertical file motion depended on the rotary speed and the resistance of the file inside the root canal and changed into a 90° rotational motion with increasing resistance. It was an attempt to make the root canal anatomy or at least the root canal diameter one main influencing factor on the behaviour of the instrument inside the canal. The Excalibur handpiece (W&H) with laterally oscillating instruments or the

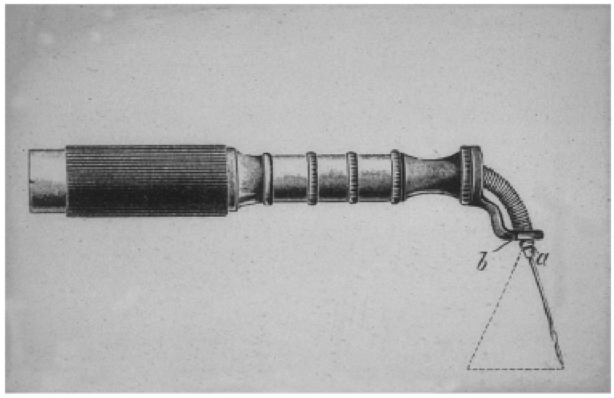

Fig. 1. Endodontic Beutelrock-bur in a handpiece with a flexible angle from 1912. Reprinted from (13) by permission by Quintessence Verlag, Berlin.

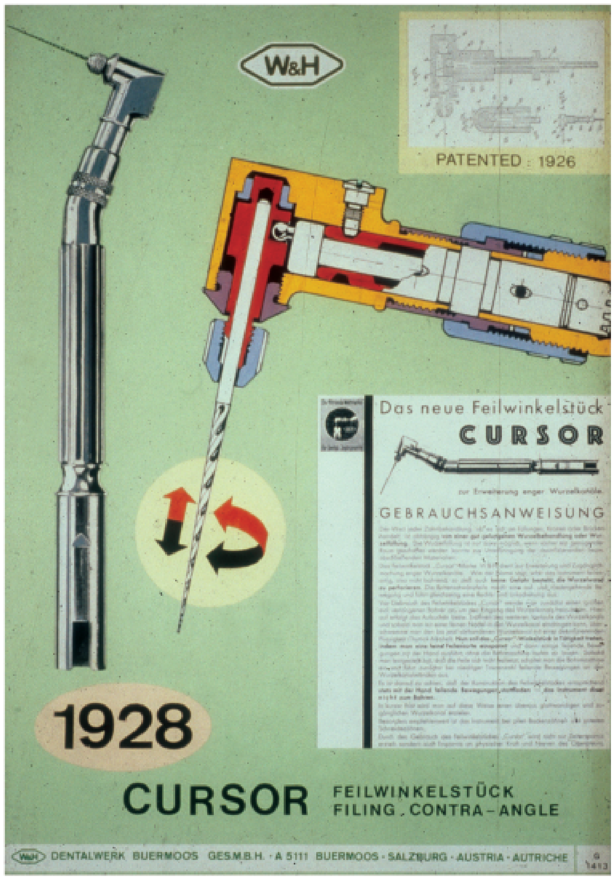

Fig. 2. Cursor-handpiece (W&H) from 1928. Reprinted from (13) by permission by Quintessence.

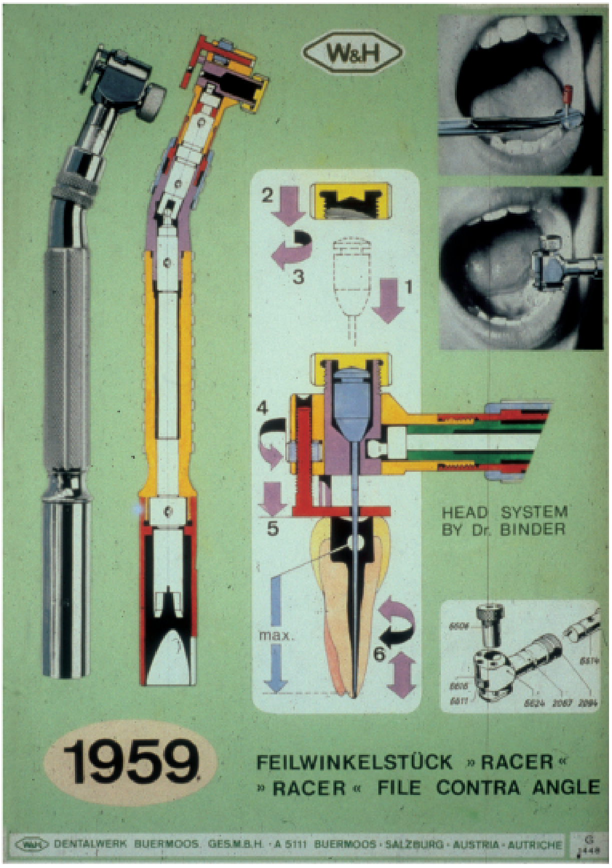

Fig. 3. Racer-handpiece (W&H) from 1959. Reprinted from (13) by permission by Quintessence.

Endoplaner (Microna, Spreitenbach, Switzerland) with an upward filing motion were further examples of handpieces with modified working motions (10, 13). Table 1 summarizes available instruments and handpieces for engine-driven root canal preparation.

Richman (15) described the use of ultrasound in endodontics but it was mainly the work of Martin & Cunningham (16) in the 1970s that made ultrasonic devices popular for root canal preparation. The first ultrasonic device was marketed in 1980, the first sonic device in 1984 (13). Since 1971 attempts have been made to use laser devices for root canal preparation and disinfection (17). Additionally, some non-instrumental or electro-physical devices have been described such as ionophoresis in several different versions, electrosurgical devices (Endox, Lysis, Munich, Germany) (18) or the non-instrumental technique (NIT) of Lussi et al. (19), using a vacuum pump for cleaning and filling of root canals.

Instruments made from nickel–titanium (NiTi), first described as hand instruments by Walia et al. (20), have had a major impact on canal preparation. NiTi rotary instruments introduced later use a 360° rotation at low speed and thus utilize methods and mechanical principles described more than 100 years ago by Rollins. While hand instruments continue to be used, NiTi rotary instruments and advanced preparation techniques offer new perspectives for root canal preparation that have the potential to avoid some of the major drawbacks of traditional instruments and devices.

Goals of mechanical root canal preparation

As stated earlier, mechanical instrumentation of the root canal system is an important phase of root canal preparation as it creates the space that allows irrigants and antibacterial medicaments to more effectiveley eradicate bacteria and eliminate bacterial byproducts. However, it remains one of the most difficult tasks in endodontic therapy.

In the literature various terms have been used for this step of the treatment including instrumentation, preparation, enlargement, and shaping.

The major goals of root canal preparation are the prevention of periradicular disease and/or promotion of healing in cases where disease already exists through:

- Removal of vital and necrotic tissue from the main root canal(s).
- Creation of sufficient space for irrigation and medication.
- Preservation of the integrity and location of the apical canal anatomy.
- Avoidance of iatrogenic damage to the canal system and root structure.
- Facilitation of canal filling.
- Avoidance of further irritation and/or infection of the periradicular tissues.
- Preservation of sound root dentine to allow long-term function of the tooth.

Techniques of root canal preparation include manual preparation, automated root canal preparation, sonic and ultrasonic preparation, use of laser systems, and NITs.

Ingle (21) described the first formal root canal preparation technique, which has become known as the 'standardized technique'. In this technique, each

Table 1. Summary of currently available systems for engine-driven systems for root canal preparation and their respecive properties

Handpiece	*Manufacturer*	*Mode of action*
Conventional systems		
Racer	Cardex, via W&H, Bürmoos, Austria	Vertical movement
Giromatic	MicroMega, Besançon, France	Reciprocal rotation (90°)
Endo-Gripper	Moyco Union Broach, Montgomeryville, PA, USA	Reciprocal rotation (90°)
Endolift	Sybron Endo, Orange, CA, USA	Vertical movement+reciprocal rotation (90°)
Endolift M 4	Sybron Endo	Reciprocal rotation (30°)
Endocursor	W&H	Rotation (360°)
Intra-Endo 3 LD	KaVo, Biberach, Germany	Reciprocal rotation (90°)
Alternator	Unknown	Reciprocal rotation (90°)
Dynatrak	Dentsply DeTrey, Konstanz, Germany	Reciprocal rotation (90°)
Flexible systems		
Excalibur	W&H	Lateral oscillations (2000 Hertz, 1.4–2 mm amplitude)
Endoplaner	Microna, Spreitenbach, Switzerland	Vertical motion+free rotation
Canal-Finder-System	S.E.T., Gröbenzell, Munich	Vertical movement (0.3–1 mm)+free rotation under friction
Canal-Leader 2000	S.E.T.	Vertical movement (0.4–0.8 mm)+partial rotation (20–30°)
Intra-Endo 3-LDSY	KaVo	Vertical motion+free rotation
IMD 9GX	HiTech, unknown	360° – rotation with variable, torque-dependent rotational speed (min 10/min)
Sonic systems		
Sonic Air 3000	MicroMega	
Endostar 5	Medidenta Int, Woodside, NY, USA	6000 Hz
Mecasonic	MicroMega	
MM 1400 Sonic Air	MicroMega	
Yoshida Rooty	W&H	6000 Hz
MM 1500 Sonic Air	MicroMega	1500–3000 Hz
Ultrasonic systems		
Cavi-Endo	Dentsply DeTrey	Magnetostrictive 25 000 Hertz
Piezon Master	EMS, Nyon, Switzerland	Piezoceramic 25 000–32 000 Hz
ENAC OE 3 JD	Osada, Tokyo, Japan	Piezoceramic 30 000 Hz

Table 1. Continued

Handpiece	*Manufacturer*	*Mode of action*
Piezotec PU 2000	Satelec, Merignac, France	Piezoceramic 27 500 Hz
Odontoson	Goof, Usserød Mølle, Denmark	Faret rod 42 000 Hz
Spacesonic 2000	Morita, Dietzenbach, Germany	
NiTi systems		
LightSpeed	Lightspeed, San Antonio TX, USA	Rotation (360°)
ProTaper	Dentsply Maillefer, Ballaigues, Switzerland	Rotation (360°)
K 3	Sybron Endo	Rotation (360°)
ProFile 0.04 and 0.06	Dentsply Maillefer	Rotation (360°), taper 0.4–0.8
Mity-Roto-Files	Loser, Leverkusen, Germany	Rotation (360°), taper 0.02
FlexMaster	VDW, Munich Germany	Rotation (360°), taper 0.02/0.04/0.05
RaCe	FKG, La-Chaux De Fonds, Switzerland	Rotation (360°)
Quantec SC, LX	Tycom, now: Sybron Endo	Rotation (360°)
EndoFlash*	KaVo	Rotation (360°)
NiTiTEE	Loser	Rotation (360°)
HERO 642	MicroMega	Rotation (360°), taper 0.02–0.06
Tri Auto ZX	Morita, Dietzenbach, Germany	360°-rotation+auto-reverse-mechanism and integrated electrical length determination
GT Rotary	Dentsply Maillefer	Rotation (360°), taper 0.04–0.12

*Initially available as stainless-steel instruments.

instrument was introduced to working length resulting in a canal shape that matched the taper and size of the final instrument. This technique was designed for single-cone filling techniques.

Schilder (1) emphasized the need for thorough cleaning of the root canal system, i.e., removal of all organic contents of the entire root canal space with instruments and abundant irrigation and coined the axiom 'what comes out is as important as what goes in'. He stated that shaping must not only be carried out with respect to the individual and unique anatomy of each root canal but also in relation to the technique of and material for final obturation. When gutta-percha filling techniques were to be used he recommended that the basic shape should be a continuously tapering funnel following the shape of the original canal; this was termed as the 'concept of flow' allowing both removal of tissue and appropriate space for filling. Schilder described five *design objectives*:

I. Continuously tapering funnel from the apex to the access cavity.
II. Cross-sectional diameter should be narrower at every point apically.
III. The root canal preparation should flow with the shape of the original canal.
IV. The apical foramen should remain in its original position.
V. The apical opening should be kept as small as practical.

And four *biologic objectives*:

I. Confinement of instrumentation to the roots themselves.

II. No forcing of necrotic debris beyond the foramen.
III. Removal of all tissue from the root canal space.
IV. Creation of sufficient space for intra-canal medicaments.

Challenges of root canal preparation

Anatomical factors

Several anatomical and histological studies have demonstrated the complexity of the anatomy of the root canal system, including wide variations in the number, length, curvature and diameter of root canals; the complexity of the apical anatomy with accessory canals and ramifications; communications between the canal space and the lateral periodontium and the furcation area; the anatomy of the peripheral root dentine (22–25) (Fig. 4). This complex anatomy must be regarded as one of the major challenges in root canal preparation and is reviewed in detail elsewhere in this issue.

Microbiological challenges

Both pulp tissue and root dentine may harbor microorganisms and toxins (26–33). A detailed description of the complex microbiology of endodontic infections lies beyond the scope of this review, this issue recently has been reviewed by Ørstavik & PittFord (34), Dahlen & Haapasalo (35), Spångberg & Haapasalo (36) and others.

Iatrogenic damage caused by root canal preparation

Weine et al. (37, 38) and Glickman & Dumsha (39) have described the potential iatrogenic damage that can occur to roots during preparation with conventional steel instruments and included several distinct preparation errors:

Zip

Zipping of a root canal is the result of the tendency of the instrument to straighten inside a curved root canal. This results in over-enlargement of the canal along the outer side of the curvature and under-preparation of the inner aspect of the curvature at the apical end point.

Fig. 4. Morphology of the apical parts of the root canal systems of a maxillary pre-molar and canine as described by Meyer (24). Reprinted from (13) by permission by Quintessence.

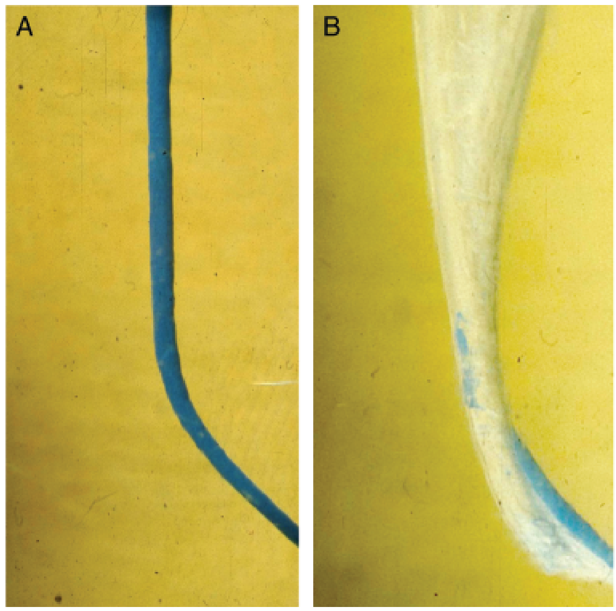

Fig. 5. (A, B) Simulated root canals in plastic blocks before and following preparation clearly demonstrate the genesis of straightening and creation of zip and elbow.

The main axis of the root canal is transported, so that it deviates from its original axis. Therefore, the terms straightening, deviation, transportation are also used to describe this type of irregular defect. The terms ‘teardrop’ and ‘hour-glass shape’ are used similarly to describe the resulting shape of the zipped apical part of the root canal (Fig. 5A, B).

Elbow

Creation of an ‘elbow’ is associated with zipping and describes a narrow region of the root canal at the point of maximum curvature as a result of the irregular widening that occurs coronally along the inner aspect and apically along the outer aspect of the curve. The irregular conicity and insufficient taper and flow associated with elbow may jeopardize cleaning and filling the apical part of the root canal (Fig. 6A, B).

Ledging

Ledging of the root canal may occur as a result of preparation with inflexible instruments with a sharp, inflexible cutting tip particularly when used in a rotational motion. The ledge will be found on the outer side of the curvature as a platform (Fig. 7), which may be difficult to bypass as it frequently is associated with blockage of the apical part of the root canal. The occurrence of ledges was related to the degree of curvature and design of instruments (40–42).

Perforation

Perforations of the root canal may occur as a result of preparation with inflexible instruments with a sharp cutting tip when used in a rotational motion (Fig. 8). Perforations are associated with destruction of the root cementum and irritation and/or infection of the periodontal ligament and are difficult to seal. The incidence of perforations in clinical treatment as well as in experimental studies has been reported as ranging from 2.5 to 10% (13, 43–46). A consecutive clinical problem of perforations is that a part of the original root canal will remain un- or underprepared if it is not possible to regain access to the original root canal apically of the perforation.

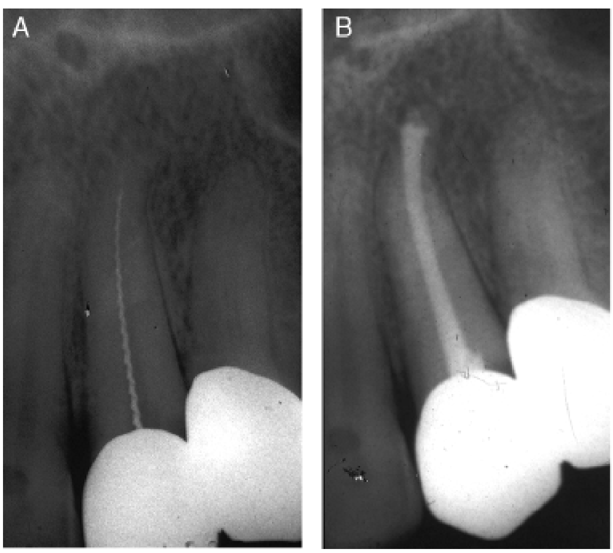

Fig. 6. Elbow formation and apical zipping in a curved maxillary canine. Reprinted by permission from Urban & Fischer, Munich.

Strip perforation

Strip perforations result from over-preparation and straightening along the inner aspect of the root canal curvature (Fig. 9). These midroot perforations are again associated with destruction of the root cementum and irritation of the periodontal ligament and are difficult to seal. The radicular walls to the furcal aspect of roots are often extremely thin and were hence termed 'danger zones'.

Outer widening

First described by Bryant et al. (47) 'outer widening' describes an over-preparation and straightening along

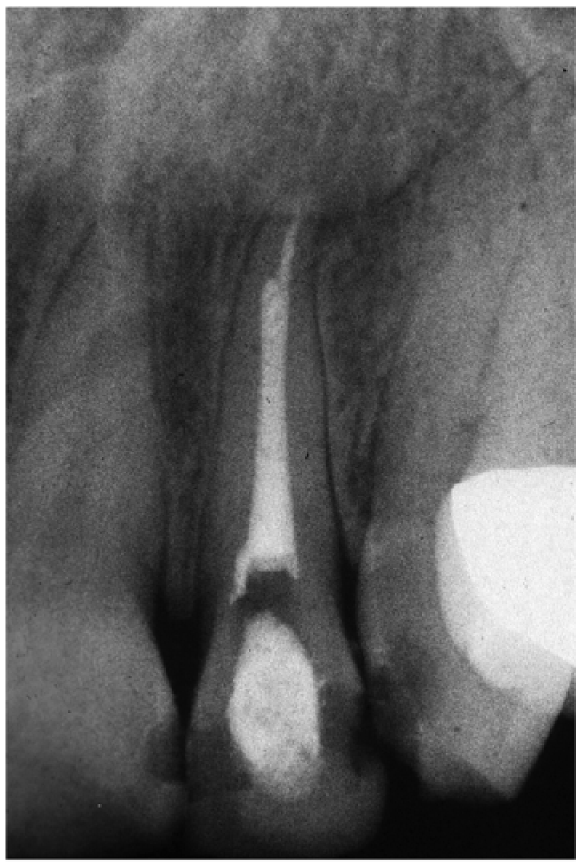

Fig. 7. Ledging at the outer side of the root canal curvature. Reprinted by permission of Quintessence.

Fig. 8. Perforation of a curved root canal.

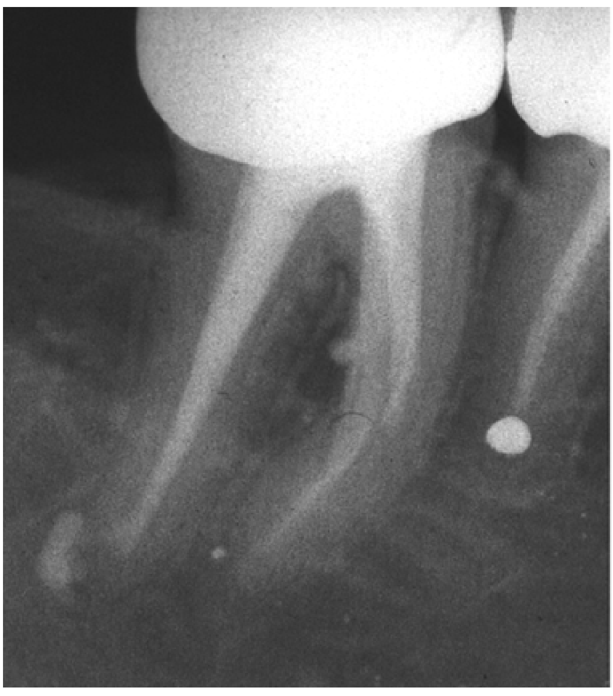

Fig. 9. Strip perforation at the inner side of the curvature.

the outer side of the curve without displacement of the apical foramen. This phenomenon until now has been detected only following preparation of simulated canals in resin blocks.

Apical blockage

Apical blockage of the root canal occurs as a result of packing of tissue or debris and results in a loss of working length and of root canal patency (Fig. 10). As a consequence complete disinfection of the most apical part of the root canal system is impossible.

Damage to the apical foramen

Displacement and enlargement of the apical foramen may occur as a result of incorrect determination of working length, straightening of curved root canals, over-extension and over-preparation. As a consequence irritation of the periradicular tissues by extruded irrigants or filling materials may occur because of the loss of an apical stop. Clinical consequences of this occurrence are reviewed elsewhere in this issue.

Besides these 'classical' preparation errors insufficient taper (conicity) and flow as well as under- or over-preparation and over- and underextension have been mentioned in the literature.

Criteria for assessment of the quality of root canal preparation

When analyzing the quality of root canal preparation created by instruments and techniques several parameters are of special interest, particularly their cleaning

Fig. 10. Apical blockage by dentine debris. Reprinted with kind permission from Quintessence, Berlin.

Table 2. Summary of possible criteria for assessment of techniques and instruments for root canal preparation, including motors and handpieces

Disinfection
Reduction of the number of microorganisms
Removal of infected dentine
Improvement of irrigation
Unprepared areas
Cleanliness of root canal walls debris
Smear layer
Preparation shape
Longitudinal
Straightening, deviation
Displacement and enlargement of the apical foramen
Zips and elbows
Taper, conicity
Flow
Over/underextension
In cross-sections
Diameter
Circumferential/cross-sectional shape
Over/under-preparation
Fins and recesses
Increase in canal area
Danger of perforation into the furcation
Canal axis movement
Three-dimensional
Straightening and transportation
Changes in volume
Canal axis movement
Safety issues
Instrument fractures
Ledges
Perforations
Excessive dentine removal
Apical blockage
Loss of working length
Extruded debris and/or irrigant
Temperature increase
Working time
Efficacy
Handling
Maintenance of digital/manual tactility
Adjustment of a stopper for length control
Insertion of instruments into handpiece
Programming the motor
Accessibility to the posterior region
Visualization during preparation
Assortment of files, quality of files, size designation
Integrated irrigation, type and amount of irrigant
Noise and vibrations of the handpiece or motor
Ergonomy and mobility of the device
Costs
Instruments
Motor or handpiece
Life-span of instruments and motor

ability, their shaping ability as well as safety issues. A detailed list of potential criteria for the assessment of the quality of root canal instruments or preparation techniques is presented in Table 2.

Methodological aspects in assessment of preparation quality

Over recent decades a plethora of investigations on manual and automated root canal preparation has been published. Unfortunately, the results are partially contradictory and no definite conclusions on the usefulness of hand and/or rotary devices can be drawn, Major deficiencies of studies on quality of root canal preparation include:

- While currently available hand instruments have been used for almost a century, no definitive mode of use has emerged as the gold standard. However, the Balanced force technique (48) may be cited as such a gold standard for *ex vivo* and clinical studies (49–51).
- In the majority of experimental studies published in the literature only a small number of rotary systems or rotary techniques are investigated and compared. Only few studies include a comparison of four (39, 50, 52–56), five (57), or six and more (13, 45, 46, 58–65) devices and techniques.
- In the majority of these published studies only some of the parameters listed in Table 2 were investigated, thus allowing only limited conclusions on a certain device, instrument or technique. The majority of studies still focus on preparation shape in a longitudinal plane, whereas the number of studies on cleaning ability remains small. This probably is because of the fact, that the investigation of both cleaning and shaping is difficult to perform in one single experimental procedure and in any case requires two different evaluations. Data on working time and working safety are usually not collected in separate experiments but rather are a side-product of investigations designed for other purposes.
- A wide variety of experimental designs and methodological considerations as well as of evaluation criteria does not allow a comparison of the results of different studies even when performed with the same device or technique.
- Many publications do not include sufficient data on sample composition, operator experience and training, calibration before assessment, e.g., photographs or electron micrographs, and on reproducibility of the results (inter- and intra-examiner agreement).
- It has been criticized that in many studies preparation protocols modified by the investigators have been introduced and evaluated rather than the preparation protocol as suggested by the manufacturer. This might result in inadequate use of instruments and techniques and lead to misleading results and conclusions.

Evaluation of post-operative root canal cleanliness

Post-operative root canal cleanliness has been investigated histologically or under the SEM using longitudinal (13, 65, 66) and horizontal (67–69) sections of extracted teeth. In horizontal sections remaining predentine, pulpal tissue and debris may be stained and the amount of remaining tissue and debris measured quantitatively (68, 69). The use of horizontal sections allows a good investigation of isthmuses and recesses but loose debris inside the canal lumen may be lost during sectioning. As well contamination of the root canal system with dust from the saw blades may occur.

The use of longitudinal sections allows nearly complete inspection of both halves of the entire main root canal. Lateral recesses and isthmuses are difficult to observe. From a technical point of view it is difficult to section a curved root, therefore it has been proposed first to cut the root into horizontal segments which then may be split longitudinally (13, 70). In horizontal sections great care must be taken to avoid contamination during the sectioning process, which may be prevented by insertion of a paper point or a gutta-percha cone.

For the assessment of root canal cleanliness in the majority of the studies two parameters have been evaluated: debris and smear layer.

Debris may be defined as dentine chips, tissue remnants and particles loosely attached to the root canal wall.

Smear layer has been defined by the American Association of Endodontists' glossary 'Contemporary Terminology for Endodontics' (71): A surface film of debris retained on dentine or other surfaces after instrumentation with either rotary instruments or endodontic files; consists of dentine particles, remnants of vital or necrotic pulp tissue, bacterial components and retained irrigant.

Further criteria may be the reduction of bacteria and the removal/presence of tissue, both of which are more difficult to assess but clinically more relevant.

Scores

The standard technique for the evaluation of post-operative root canal cleanliness is the investigation of root segments under the SEM. For this purpose several different protocols have been described. Some of these studies are only of descriptive nature (53, 54, 72–75), others use predefined scores. These scoring systems include such with three scores (76–80), four scores (55, 64, 81–85), five scores (13, 65, 86–88), or even seven scores (89). From the majority of these publications it does not become clear, whether the specimens had been coded and the examiner blinded before the SEM investigation, preventing the identification of the preparation instrument or technique under the SEM. Furthermore, only in a few studies was the reproducibility of the scoring described (65).

Additionally, the magnifications used under the SEM differ widely, in some studies respective data are not presented at all or different magnifications were used during the investigation. A certain observer bias may occur under the SEM when working with higher magnifications, as only a small area of the root canal wall can be observed. This area may be adjusted on the screen by chance or be selected by the SEM operator. It is a common finding that most SEM operators tend to select clean canal areas with open dentinal tubules rather than areas with large bulk of debris.

Not surprisingly, in most studies root canal cleanliness has been demonstrated to be superior in the coronal part of the root canal compared with the apical part (13). Therefore an evaluation procedure specifying the results for different parts of the root canal seems preferable.

Evaluation of post-operative root canal shape

The aim of studies on post-operative root canal shape is to evaluate the conicity, taper and flow, and maintenance of original canal shape, i.e., to record the degree and frequency of straightening, apical transportation, ledging, zipping and the preparation of teardrops and elbows as described by Weine et al. (37, 38). In the past investigations on post-operative root canal shape have been performed using extracted teeth or simulated root canals in resin blocks but this parameter can be assessed clinically as well (90).

Simulated root canals in resin blocks

The several investigations on the shaping ability of instruments and techniques for root canal preparation have been performed using simulated root canals in resin blocks (54, 91–106).

The use of simulated resin root canals allows standardization of degree, location and radius of root canal curvature in three dimensions as well as the 'tissue' hardness and the width of the root canals. Techniques using superimposition of pre- and post-operative root canal outlines can easily be applied to these models thus facilitating measurement of deviations at any point of the root canals using PC-based measurement or subtraction radiography. This model guarantees a high degree of reproducibility and standardization of the experimental design. It has been suggested that the results of such studies may be transferred to human teeth (107–109).

Nevertheless, some concern has been expressed regarding the differences in hardness between dentine and resin. Microhardness of dentine has been measured as 35–40 kg/mm^2 near the pulp space, while the hardness of resin materials used for simulated root canals is estimated to range from 20 to 22 kg/mm^2 depending on the material used (38, 110–112). For the removal of natural dentine double the force had to be applied than for resin (107). Additionally, it has been criticized that the size of resin chips and natural dentine chips may be not identical, resulting in frequent blockages of the apical root canal space and difficulties to remove the debris in resin canals (38, 107). In consequence, data on working time and working safety from studies using resin blocks may not be transferable to the clinical situation.

Human teeth

The reproduction of the clinical situation may be regarded as the major advantage of the use of extracted human teeth, in particular when set-up in a manikin. On the other hand, the wide range of variations in three-dimensional root canal morphology makes standardization difficult. Variables include root canal length and width, dentine hardness, irregular calcifications or pulp stones, size and location of the apical constriction and in particular angle, radius, length and location of root canal curvatures including the three-dimensional nature of curvatures.

Studies on post-operative root canal shape or changes in root canal morphology, respectively, have been performed in mesial root canals of mandibulary molars, as these teeth in most cases show a curvature at least in the mesio-distal plane (113). Several techniques have been developed to determine the characteristics of the curvature, the most frequently used described by Schneider (114). It measures the degree of the curvature in order to categorize root canals as straight (5° curvature or less), moderately (10–20°) or severely curved (> 20°). More advanced techniques (115–119) aim to determine degree and radius as well as length and location of the curve(s), since all of these factors may influence the treatment/preparation outcome.

Early studies on preparation shape were conducted using replica techniques (120–124), which are suited to demonstrate post-operative taper and flow, smoothness of root canal walls and quality of apical preparation. As the original shape of the root canals remains unknown the difference between pre- and post-operative shape cannot be evaluated with such techniques.

Bramante et al. (125) were the first to develop a method for the evaluation of changes in cross-sectional root canal shapes. They imbedded extracted teeth in acrylic resin blocks and constructed a plaster muffle around this resin block. After sectioning the imbedded teeth horizontally the resulting slices were reset into the muffle for instrumentation. Pre- and post-instrumentation photographs of the root canal diameter could be superimposed and deviations between the two root canal outlines could be measured. Subsequently, improved versions of the 'Bramante technique' were descibed (66, 126–130). The quantification of post-operative root canal deviation may be performed using the 'centring ratio' method (126, 131–134) or via measurement of the pre- and post-operative dentine thickness (135). This method also allows evaluation of circular removal of predentine and cleanliness of isthmuses and recesses (136, 137).

Recent technologies include the use of high-resolution tomography and micro-computed tomography (CT) (50, 138–143). This non-destructive technique allows measurement of changes in canal volume and surface area as well as differences between pre- and post-preparation root canal anatomy. The advantages of these techniques are three-dimensional replication of the root canal system, the possibility of repeated measurements (pre-, intra- and post-operative) and the computer aided measurement of differences between two images. The use of micro-CT additionally enables the evaluation of the extent of unprepared canal surface and of canal transportation in three dimensions (Fig. 11).

Apical extrusion of debris

Measurements of the amount of debris extruded apically through the apical constriction were mostly conducted by collecting and weighing this material during preparation of extracted teeth (13, 70, 144–154). It must be noted that such techniques are unreliable for several reasons: working on extracted teeth there is no resistance from the periradicular tissues preventing the flow of irrigants through the foramen. The way the debris is collected and drying and weighing procedures also may have some (unknown) influence on the results. The results from the various studies, some of which were conducted without irrigation during preparation, show a wide range of results from 0.01 mg to 1.3 g (13). Moreover, Fairbourn et al. (145) reported an extrusion of 0.3 mg during hand filing to a size #35 including irrigation, while Myers & Montgomery (148) found extrusion of 0.01–0.69 mg during hand filing to size #40 including irrigation.

From these studies it can be concluded that it is unlikely to prepare a root canal system chemo-mechanically without any extrusion of debris (44). The amount of extruded debris probably depends on the apical extent of preparation (144, 148). As it is not known to which degree the extruded material is infected and which amount is tolerated by the periapical tissues, the clinical relevance of such data must remain questionable. Phagocytosis of small amounts of debris has been reported (155–157); however, extruded material has been held responsible for post-operative flare-ups and bacteraemia (158–160).

Evaluation of safety issues

The main safety issues reported in studies on root canal preparation concern instrument fractures, apical blockages, loss of working length, ledging, perforations, rise of temperature, and apical extrusion of debris. Most of these issues have not been investigated systematically in specially designed investigations.

In some retrospective evaluations of endodontically treated teeth an incidence of instrument separation in 2–6% of the cases has been reported (161–165). Instrument fractures may be related to the type, design and quality of the instruments used, the material they are manufactured from, rotational speed and torque, pressure and deflection during preparation, the angle

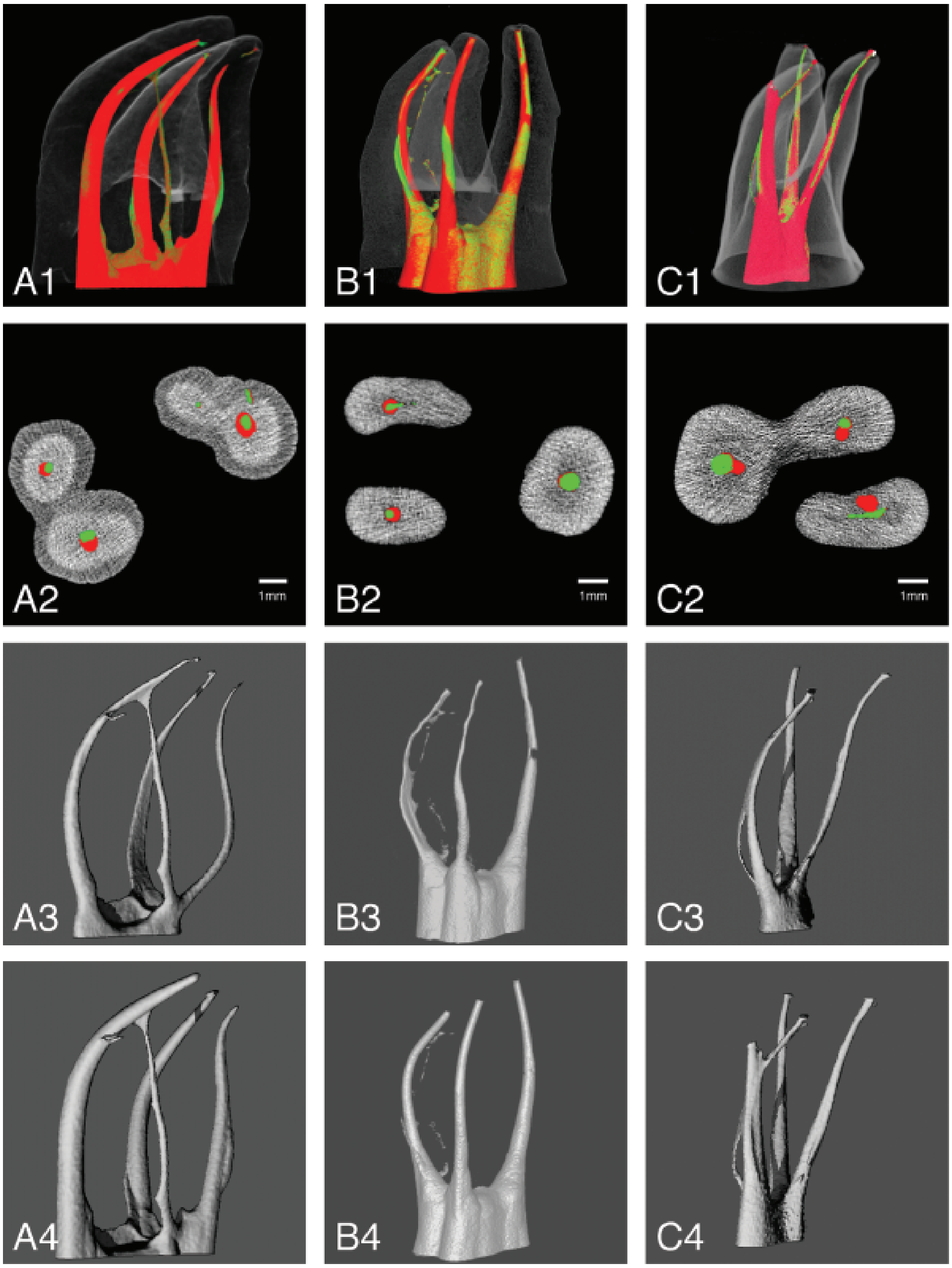

Fig. 11. Three root canal preparation techniques (columns A–C) analysed by micro-CT. Reconstruction of three-dimensional canal models (rows 1, 3, 4 and cross-sections (row 2) with pre-operative canals in green and postoperative shapes in red. Reprinted from (327) by permission of the Journal of Endodontics (30: 569, 2004).

and radius of the root canal curvature, frequency of use, sterilization technique and probably various other factors, in particular the operators' level of expertise.

No systematic investigations of instrument fracture of conventional steel instruments or conventional automated devices could be found in the literature, but because of their design Hedström files seem to be more prone to fracture than other instruments (166–168). A high number of fractures were reported in *ex vivo* studies of rotary NiTi instruments but the clinical incidence of such fractures has not yet been investigated.

Evaluation of working time

The aim of the evaluation of working time for any instrument or technique is to draw conclusions on the efficacy of the device or technique and on its clinical suitability. Data on working time show large differences for identical instruments and techniques, which is because of methodological problems as well as to individual factors.

Therefore, data from different studies should be compared with caution, as variation caused by individuals (169) cannot be defined exactly but should be regarded as decisive in many cases. For example, it was demonstrated that instrument fractures resulted in longer working times for the following instruments in order to avoid additional fractures (170, 171).

For the evaluation of the efficacy of an instrument the measurement of the cutting ability therefore seems to more appropriate (172, 173). Theses studies use an electric motor driving the root canal instrument into natural root canals in extracted teeth or artificial canals in resin blocks, thus excluding individual factors. However, this does not exactly mirror the clinical situation either.

In the recent past four major series of standardized comparative investigations on rotary NiTi instruments have been published. These will be briefly reviewed.

The Cardiff experimental design

This series of investigations (97–106, 174–177) was performed in simulated root canals. Four types of root canals were constructed using size #20 silver points as templates. The silver points were pre-curved with the aid of a canal former, to form four different canal types in terms of angle and location. The four canal types were:

Curvature 20°, beginning of the curvature 8 mm from the orifice.
Curvature 40°, beginning of the curvature 12 mm from the orifice.
Curvature 20°, beginning of the curvature 8 mm from the orifice.
Curvature 40°, beginning of the curvature 12 mm from the orifice.

The following variables and events were recorded and evaluated: preparation time, instrument failure (deformation and fracture), canal blockage, loss of working distance, transportation, canal form (apical stop, smoothness, taper and flow, aberrations (zips, elbows, ledges, perforations, danger zones), canal width.

The Zürich experimental design

In a series of investigations (50, 138–143) the Zürich group used high-resolution or micro-CT to measure changes in canal volume and surface area as well as differences between pre- and post-preparation root canal anatomy. The advantages of this non-destructive technique are three-dimensional replication of the root canal system, the possibility of repeated measurements (pre-, intra- and post-operative), and the computer-aided measurement of differences between two images. The use of micro-CT enables the evaluation of changes in volume and surface area of the root canal system, the extent of unprepared canal surface and canal transportation in three dimensions (Fig. 11). Similar experiments by other groups have since corroborated and expanded the findings cited above.

In this system, maxillary molars are embedded into resin and mounted on SEM stubs, in order to allow reproducible positioning into the micro-CT. This approach in conjunction with specific software renders high reproducibility (139) and allows comparisons of pre- and post-operative canal shapes with accuracy approaching the voxel size (currently 18–36 μm). Specimens are then further characterized with respect to pre-operative canal anatomy (volume, curvature) and divided into statistically similar experimental groups. Analyses can then be carried out with software that separates virtual root canals, automatically detects the canal axis and its changes after preparation and the amount of preparared root canal surface area.

The Göttingen experimental design

This series of investigations (13, 91, 92, 137, 170, 171, 178–183) on conventional endodontic handpieces as well as on several rotary NiTi systems made use of a modified version of Bramante's muffle model (125).

A muffle block is used allowing removal and exact repositioning of the complete specimen or sectioned parts of it. A modification of a radiographic platform, as described by Sydney et al. (184) and Southard et al. (185), may be adjusted to the outsides of the middle part of the muffle. This allows radiographs to be taken under standardized conditions, so that these radiographs, taken before, during and after root canal preparation may be superimposed. A pre-fabricated stainless-steel crown may be inserted at the bottom of the middle part of the muffle system to collect apically extruded debris (Fig. 12A, B).

After embedding, mesio-buccal canals of extracted mandibular molars with two separate patent mesial root canals are prepared. Root canal straightening, working time and working safety are recorded by superimposition of radiographs taken under standardized conditions. Following this the tooth block is separated into four parts with a saw, the crown and three segments with the roots. After taking standardized photographs of the pre-operative cross-section of the mesio-lingual root canal this is prepared. Again photographs of the cross-section are taken, allowing superimposition of both pre- and post-operative canal circumference and evaluation of changes in cross-section. Additionally, the percentage of unprepared root canal wall areas can be measured. Again working time and procedural incidents are recorded. The three root segments finally are split longitudinally and the cleanliness of the root canal walls is evaluated under SEM using five scores for separate evaluation of remaining debris (magnification $\times 200$) and smear layer ($\times 1000$) (65).

While Bramante et al. (125) originally intended to evaluate changes in cross-sectional diameter, this model allows the parallel investigation of several important parameters of root canal preparation: straightening in the longitudinal axis, changes in root canal diameter (horizontal), root canal cleanliness, working time, and safety issues. Initially, an attempt was made to collect and weigh the apically extruded debris too, but this part of the model produced unreliable results. Shortcomings of this model are related mainly to the irregularities in human root canal anatomy and morphology.

The Münster experimental design

This recent series of investigations on several rotary NiTi systems (186–194) uses two types of plastic blocks with different degrees of curvature (28° and 35°) for the evaluation of straightening and working safety as well as extracted teeth with severely curved root canals (25–35°) for the evaluation of root canal cleanliness, working safety and working time.

Manual preparation techniques

Several different instrumentation techniques have been described in the literature, a summary of some more popular techniques is presented in Table 3. Some of these techniques use specially designed instruments (e.g., the Balanced force technique was described for Flex-R instruments).

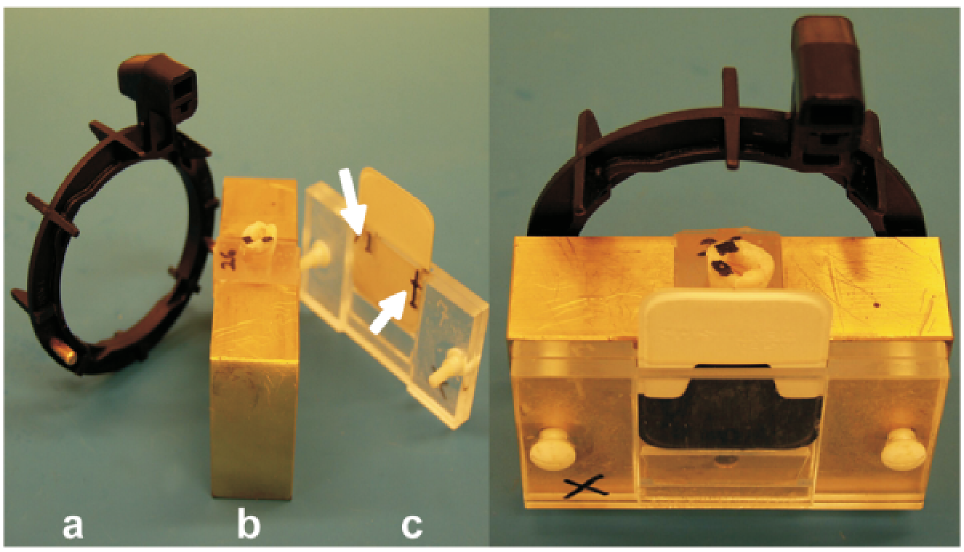

Fig. 12. (a, b) Parts of the muffle system from the Göttingen studies (a–c). After removal of the outer parts of the muffle system a film holder (a) and a holder for reproducible attachment of the X-ray beam (c) can be adjusted to the middle part of the muffle (b) containing the prepared tooth. Two metal wire are integrated into the film holder, allowing exact superimposition of the radiograph (arrows).

Table 3. Summary of manual root canal preparation techniques described in the literature

Approach	Author(s)	References
Standardized technique	Ingle (1961)	(21)
Step-back technique	Clem (1969)	(195)
Circumferential filing	Lim & Stock (1987)	(196)
Incremental technique	Weine et al. (1970)	(197)
Anticurvature filing	Abou-Rass et al. (1980)	(198)
Step-down technique	Marshall & Papin (1980)	(199)
Step-down technique	Goerig et al. (1982)	(200)
Double flare technique	Fava (1983)	(201)
Crown-down-pressureless technique	Morgan & Montgomery (1984)	(123)
Balanced force technique	Roane et al. (1985)	(48, 202)
Canal Master technique	Wildey & Senia (1989)	(204, 205)
Apical box technique	Tronstad (1991)	(206)
Progressive enlargement technique	Backman et al. (1992)	(207)
Modified double flare technique	Saunders & Saunders (1992)	(208)
Passive stepback technique	Torabinejad (1994)	(209, 210)
Alternated rotary motions-technique (ARM)	Siqueira et al. (2002)	(211)
Apical patency technique	Buchanan (1989)	(212)

Manual preparation techniques and results of studies

Balanced force technique

This technique, reported by Roane & Sabala in 1985 (48, 202), was originally associated with specially designed stainless-steel or NiTi K-type instruments (Flex-R-Files) with modified tips in a stepdown manner. Instruments are introduced into the root canal with a clockwise motion of maximum 180° and apical advancement (placement phase), followed by a counterclockwise rotation of maximum 120° with adequate apical pressure (cutting phase). The final removal phase is then performed with a clockwise rotation and withdrawal of the file from the root canal. Apical preparation is recommended to larger sizes than with other manual techniques, e.g., to size #80 in straight canals and #45 in curved canals. The main advantages of the Balanced force technique are good apical control of the file tip as the instrument does not cut over the complete length, good centring of the instrument because of the non-cutting safety tip, and no need to pre-curve the instrument (2).

Roane & Sabala (48) themselves and further studies (49, 50, 131, 185, 203, 207, 208, 213–217) described good results for the preparation of curved canals without or with only minimal straightening. However, others reported a relatively high incidence of procedural problems such as root perforations (218) or instrument fractures (219). The amount of apically extruded debris was less than with stepback or ultrasonic techniques (147, 150, 220), the apical region showed good cleanliness (221). Varying results were reported for the amount of dentine removed; in one study the Balanced force technique performed superior compared with the stepback technique (126), while in another study more dentine was removed 1 mm from the apex when using the stepback technique (222). When used in a double-flared sequence canal area after shaping was larger than after preparation with Flexogates or Canal Master U-instruments (223).

Post-instrumentation area was also greater in comparison with Lightspeed preparation (224), following ultrasonic preparation or rotary Canal Master preparation and equal to hand preparation using the stepback technique (49). A comparison of NiTi K-files used in Balanced forces motion to current rotary instrument systems indicated similar shaping abilities (50). However, some earlier reports had indicated significantly more displacement of the root canal centres, suggesting straightening (224, 225).

Cleanliness was rated superior compared with the crowndown pressureless and stepback techniques (76). The Balanced force technique required more working time than preparation with GT Rotary, Lightspeed or ProFile NiTi instruments (217, 225).

Stepback vs. stepdown

Stepback and stepdown techniques for long have been the two major approaches to shaping and cleaning procedures. Serial, telescopic or stepback techniques commence preparation at the apex with small instruments. Following apical enlargement instrumentation length may be reduced with increasing instrument size. Stepdown techniques commence preparation using larger instrument sizes at the canal orifice, working down the root canal with progressively smaller instruments. Major goals of crowndown techniques are reduction of periapically extruded necrotic debris and minimization of root canal straightening. Since during the stepdown there is less constraint to the files and better control of the file tip it has been expected that apical zipping is less likely to occur. Over the years several modifications of these techniques have been proposed, such as the crowndown technique, as well as hybrid techniques combining an initial stepdown with a subsequent stepback (modified double flare) (Table 3).

Although stepback and stepdown techniques may be regarded as the traditional manual preparation techniques there are surprisingly few comparative studies on these two techniques. There is no definite proof that 'classical' stepdown techniques are superior to stepback techniques. Only the Balanced force technique, which is a stepdown technique as well, has been shown to result in less straightening than stepback or standardized techniques (126, 207, 219).

In a comparative study of four preparation techniques no difference between stepback and crowndown was detected in terms of straightening, but crowndown produced more ledges (117). Using the Balanced force technique, the apical part of curved root canals showed less residual debris than following preparation with the crowndown pressureless or stepback technique (76) although stepback preparation resulted in a larger increase in canal diameter and more dentine removal than Balanced force preparation (222).

Crowndown techniques have been reported to produce less apically extruded debris than stepback preparation (146, 147, 152, 216).

Conventional rotary systems

In an extensive series of experiments the Göttingen group compared preparation quality, cleaning ability and working safety of different conventional endodontic handpieces (13). The study involved a total of 15 groups each with 15 prepared teeth. Devices and techniques evaluated included the Giromatic with two different files, Endolift, Endocursor, Canal-Leader with two different files, Canal-Finder with two different files, Intra-Endo 3-LDSY, manual preparation, Excalibur, Endoplaner, Ultrasonics and the Rotofile NiTi instruments (in other countries known as MiTy-Roto-Files). Mean root canal curvature of the different groups in this study was between 17.8° and 25.1°, all root canals were enlarged to size #35. Further studies were performed on the Excalibur (226) and the Endoplaner.

Taken together, these studies demonstrated that preparation of curved root canals using conventional automated devices with stainless-steel instruments in many cases resulted in severe straightening. Similar results earlier already had been found in studies on the

- Endolift (13, 52, 54, 63).
- Endolift M4 (227, 228).
- Endocursor (39, 122, 229).
- Excalibur (45, 46, 63, 226, 230–231).
- EndoGripper (228).
- Intra-Endo 3-LDSY (45, 46, 63, 232).
- Endoplaner (63).
- Giromatic (39, 52, 54, 70, 122, 233–238).
- Canal-Finder System (13, 54, 63, 72, 74, 85, 92, 128, 239–241). In some studies the Canal-Finder straightened less than or equal to hand instrumentation (59, 242–244).

- Canal-Leader (13, 241, 245, 246).
- Ultrasonics (13, 53, 54, 59, 241, 247–254).

Few studies have been published on post-operative root canal cleanliness after preparation with the devices mentioned above. The majority of these reported on large agglomerations of debris and smear layer covering almost the complete root canal wall (54, 61, 64, 64, 85, 230, 232, 255). In some studies slightly superior results were found for automated systems with integrated water supply, for example the Canal Finder and the Canal Leader (65, 75, 256).

Additionally, for some of the automated devices severe problems concerning safety issues (apical blockages, loss of working length, perforations and instrument fractures) have been reported (13, 54, 58, 59, 63, 94, 110, 111, 152, 226, 227, 230, 237, 243, 257–263).

NiTi systems

Metallurgical aspects

Several metallurgical aspects of NiTi instruments have been extensively reviewed previously (264–266). Two of the main characteristics of this alloy, composed of approximately 55% (wt) nickel and 45% (wt) titanium are memory shape and superior elasticity. The elastic limit in bending and torsion is two to three times higher than that of steel instruments. The modulus of elasticity is significantly lower for NiTi alloys than for steel, therefore much lower forces are exerted on radicular wall dentine, compared with steel instruments. These unique properties are related to the fact that NiTi is a so-called 'shape memory alloy', existing in two different crystalline forms: austenite and martensite. The austenitic phase transforms into the martensitic phase on stressing at a constant temperature and in this form needs only light force for bending. After release of stresses the metal returns into the austenitic phase and the file regains its original shape. Because of the metallic properties of NiTi, it became possible to engineer instruments with greater tapers than 2%, which is the norm for steel instruments (266).

Instrument designs

Over the years several different NiTi systems have been designed and introduced on the market (see Table 1). This review does not aim at a detailed presentation, description and analysis of specific instrument designs, but it should be kept in mind that design features such as cutting angle, number of blades, tip design, conicity and cross-section, will influence the instruments' flexibility, cutting efficacy, and torsional resistance. Design and clinical usage of some of these NiTi systems are described in detail elsewhere in this issue.

Motor systems

Initially, NiTi instruments were used in regular low-speed dental handpieces, which resulted in a clinically unacceptable number of instrument fractures. In consequence, special motors with constant speed and constant torque were introduced for use with these instruments (Table 4). Earlier concepts preferring high-torque motors were followed by development of low-torque motors, some of which have several special features as auto start/stop, auto apical reverse in combination with an electronic device for determination of working length, auto torque stop, auto torque reverse, handpiece calibration, twisting motion and programmed file sequences for primary preparation and retreatment.

Initially, high-torque motors were preferred in order to allow efficient cutting of dentine and to prevent locking of the instrument. However, the incidence of instrument fractures was relatively high with these motors. The rationale for the use of low-torque or controlled-torque motors with individually adjusted torque limits for each individual file is to keep the instrument working below the limit of instrument elasticity without exceeding the instrument-specific torque limit thus reducing the risk of instrument fracture (267). The values should range between the martensitic start clinical stress and the martensitic finish clinical stress, which is dependent on design and taper of the individual instrument.

On the other hand, current norms stipulate the measurement of torque at failure at D3, a distance of 3 mm from the tip of the instrument. For an instrument with a taper of 0.06 and larger, it becomes difficult to determine a torque that is sufficient to rotate the larger more coronal part of the instrument efficiently while not endangering the more fragile apical part. In fact, it has been suggested repeatedly that the creation of a glide path allows the apical end of the instrument to act as a passive pilot and thus protects the instrument from breakage even with high torque.

Table 4. Endodontic motors for root canal preparation using Ni–Ti instruments

Motor	Company		Torque values	NiTi systems
Nouvag TCM 3000	Nouvag, Goldbach, Switzerland	High torque	5 values: 10/20/35/45/55 N cm	All systems
Nouvag TCM Endo	Nouvag	Low torque	1.0 N cm, -(no limit)-	All systems
Nouvag TCM Endo V*	Nouvag	Low torque	10 values: 0.2–5.0 N cm	All systems
EndoStepper	Komet, Lemgo, Germany	Right torque	Individual for any file	All systems
IT control	VDW	Right torque	Individual for any file	All systems
E-master	VDW	Right torque	Individual for any file; 10 values: 0.2–3.0 N cm	Only FlexMaster
ATR Tecnika	Dentsply, La Pistoia, Italy,	Low torque	Individual for any file	All systems
K3-etcm	Kerr, Karlsruhe, Germany	Low torque	5 values: <0.5, <0.9, 1.2, 1.7, 2.0 N cm	K3
Surgimotor III	Aseptico, Woodville, NJ, USA		5 values	All systems
Quantec ETM	Sybron Endo			Quantec, K3
TriAuto ZX*	Morita, Tokio, Japan	Low torque	7 values	All systems
Dentaport*	Morita, Tokio, Japan	Low torque	11 values	All systems
ENDOflash	KaVo	Low torque	3 values: 0.05, 0.09, 0.14 N cm	All systems
ENDOadvance	KaVo	Low torque	4 values: 0.25, 0.5, 1.0, 3.0 N cm	All systems
Anthogyr-handpiece	Dentsply, Ballaigues, Switzerland	Low torque	4 values: <1, 1, 2.25, <4.5 N cm	All systems
Endy 5000*	Ionyx, Blanquefort, France	Low torque		All systems
Endo-Mate TC	NSK Europe, Frankfurt, Germany,	Low torque	6 values: 0.7, 1.5, 2.3, 3.0, 3.7, 4.5 N cm	All systems
Tascal-handpiece	Max-Dental, Augsburg, Germany	Undefined	Handpiece for prophylaxis	Lightspeed
SiroNiti- handpiece	Sirona, Breitenbach, Germany	Low torque	5 values	All systems

Please note, that some of these motors are distributed in some countries under different names and by different distributors.
*Combined with electrical root canal length measurement device.
Due to higher rotational speed not all motors are suited for use with Lightspeed.

Table 5. Brief summary of investigations comparing various NiTi instruments regarding their shaping ablitity

Author(s)	References	Year	NiTi system	Method	Result
Esposito & Cunningham	(273)	1995	Mac-Files, hand & rotary	Extracted teeth	NiTi superior to K-Flex manual
Glosson et al.	(274)	1995	Lightspeed, Mity manual	Extracted teeth	LS superior to Mity man. and K-Flex manual
Knowles et al.	(275)	1996	Lightspeed	Extracted teeth	Little or no transportation
Gambill et al.	(134)	1996	Mity-files	Extracted teeth	Superior to K-Flex manual
Coleman et al.	(276)	1996	Ni–Ti–K-files vs.steel files	Extracted teeth	Ni–Ti superior with minimal straightening
Zmener & Banegas	(277)	1996	ProFile 0.04	Resin blocks	Superior to ultrasonics and K-files
Chan & Cheung	(278)	1996	Mity-files	Resin blocks	Superior to K-files
Tharuni et al.	(279)	1996	Lightspeed	Resin blocks	Superior to K-files
Short et al.	(225)	1997	ProFile 0.04, Lightspeed, McXim	Extracted teeth	All superior to Flex-R
Thompson & Dummer	(103, 104)	1997	Lightspeed	Resin blocks	Minimal transportation
Thompson & Dummer	(280, 281)	1997	NT Engine, McXim	Resin blocks	Minimal transportation
Thompson & Dummer	(99, 100)	1997	ProFile 0.04, series 29	Resin blocks	Little transportation
Bryant et al.	(97, 98)	1998	ProFile 0.04 with ISO tips	Resin blocks	Little straightening, some zips
Coleman & Svec	(282)	1997	NiTi-K-Files vs. steel files	Resin blocks	NiTi sig. less straightening, better centering
Thompson & Dummer	(174)	1998	Mity Roto, Naviflex	Resin blocks	No difference, little straightening, many ledges
Thompson & Dummer	(105, 106)	1998	Quantec Series 2000	Resin blocks	More aberrations by larger instruments
Kavanagh & Lumley	(283)	1998	ProFile 0.04 & 0.06	Extracted teeth	No difference, little or no transportation
Shadid et al.	(224)	1998	Lightspeed	Extracted teeth	Superior to Flex-R
Schäfer & Fritzenschaft	(194)	1999	HERO 642	Resin blocks	HERO 642 superior to ProFile 0.04 superior to K-Flexofiles
			ProFile 0.04		
Bryant et al.	(175)	1999	Combination of ProFile 0.04 and 0.06	Resin blocks	Adequate shape with little straightening
Ottosen et al.	(284)	1999	ProFile 0.04 vs. Naviflex	Extracted teeth	Little transportation, no difference

Table 5. Continued

Author(s)	References	Year	NiTi system	Method	Result
Kum et al.	(285)	2000	ProFile 0.0 & GT Rot. vs. steel files	Resin blocks	Ni–Ti superior to K-Flexofiles
Jardine & Gulabivala	(286)	2000	McXIM	Extracted teeth	Equal to Flexofiles manual
			ProFile 0.04	Extracted teeth	Equal to Flexofiles manual
Thompson & Dummer	(101-102)	2000	HERO 642	Resin blocks	Few aberrations
Griffiths et al.	(176)	2000	Quantec LX	Resin blocks	Outer widening in 55–80%
Griffiths et al.	(177)	2001	Quantec SC	Resin blocks	Severe aberrations after instr. no.7, outer widening
Gluskin et al.	(287)	2001	GT Rotary vs. Flexofiles	Extracted teeth	Little transportation, superior to Flexofiles
Bertrand et al.	(288)	2001	HERO 642	Extracted teeth	Little transportation, superior to steel hand files
Peters et al.	(140)	2001	Lightspeed, ProFile 0.04, GT Rotary	Extracted teeth	Little transportation
Hülsmann et al.	(178)	2001	HERO 642 vs. Quantec SC	Extracted teeth	No difference, little or no transportation
Calberson et al.	(289)	2002	GT Rotary	Resin blocks	Little transportation
Bergmans et al.	(290)	2002	Lightspeed vs. GT Rotary	Extracted teeth	No difference, little transportaion
Schäfer & Lohmann	(187)	2002	FlexMaster vs. K-Flexofile	Resin blocks	Minimal transportation, superior to K-Flexofiles
Schäfer & Lohmann	(188)	2002	FlexMaster vs. K-Flexofile	Extracted teeth	FlexMaster superior to K-Flexofiles
Versümer et al.	(179)	2002	ProFile 0.04 vs. Lightspeed	Extracted teeth	No difference, little or no transportation
Hülsmann et al.	(180)	2003	FlexMaster vs. HERO 642	Extracted teeth	No difference, little or no transportation
Weiger et al.	(291)	2003	FlexMaster vs. Lightspeed	Extracted teeth	Little transportation, Lightspeed superior to FM
Hübscher et al.	(143)	2003	FlexMaster	Extracted teeth	Little transportation
Schäfer & Florek	(189)	2003	K 3	Resin blocks	Little transportation, superior to K-Flexofiles
Schäfer & Schlingemann	(190)	2003	K 3	Extracted teeth	Little transportation, superior to K-Flexofiles
Peters et al.	(292)	2003	ProTaper	Extracted teeth	Little transportation
Bergmans et al.	(293)	2003	ProTaper vs. K3	Extracted teeth	Little transportation

Table 5. Continued

Author(s)	References	Year	NiTi system	Method	Result
Hülsmann et al.	(181)	2003	Lightspeed vs. Quantec SC	Extracted teeth	No difference, little or no transportation
Braun et al.	(294)	2003	ProFile, FlexMaster. K-Files	Extracted teeth	ProFile & FlexMaster superior to K-files
Veltri et al.	(295)	2004	GT Rotary vs. ProTaper	Extracted teeth	No difference, little or no transportation
Schäfer & Vlassis	(191)	2004	ProTaper vs. RaCe	Extracted teeth	RaCe sign. better than ProTaper
Schäfer & Vlassis	(192)	2004	ProTaper vs. RaCe	Resin blocks	RaCe superior to ProTaper
Paque et al.	(170)		ProTaper vs. RaCe	Extracted teeth	No difference, little or no transportation

However, in a comparative study of a low-torque (<1 N/cm) and a high-torque (>3 N/cm) motor with used rotary NiTi instruments the former yielded significantly higher resistance to cyclic fatigue compared with usage at high torque (268).

It should be noted in this context that systematic comparative studies of different endodontic motors are missing. This is also at least in part because of current norms that do not mirror the clinical situation for rotary instruments and the scarcity of adequately controlled experiments.

Studies on root canal preparation using NiTi systems

Cleaning ability

Studies on various NiTi instruments (Table 5) in the last years have focused on centring ability, maintenance of root canal curvature, or working safety of these new rotary systems; only relatively little information is available on their cleaning ability. It should be mentioned that the term ‘canal cleaning’ is used in this review for the ability to remove particulate debris from root canal walls with cleaning and shaping procedures. This property usually has been determined using scanning electron micrographs (for a review see (13)).

For example, the results for Quantec instruments were clearly superior to hand instrumentation in the middle and apical third of the root canals with the best results for the coronal third of the root canal. In many specimens only a thin smear layer could be detected with many open dentinal tubules (81). Kochis et al. (269) could find no difference between Quantec and manual preparation using K-files. Peters et al. (270) and Bechelli et al. (271) described a homogeneous smear layer after Lightspeed preparation. In a further study no differences between Quantec SC and Lightspeed could be found (181), both systems showed nearly complete removal of debris but left smear layer in all specimens. In the majority of specimens in both groups cleanliness was clearly better in the coronal than in the apical part of the root canals. The results are comparable with those in previous studies (178–180). However, in the latter studies EDTA was used only as a paste during preparation but a final irrigation with a liquid EDTA solution may increase the degree of cleanliness. In contrast, FlexMaster, ProTaper and HERO 642 showed nearly complete removal of debris, leaving only a thin smear layer with a relatively high percentage of specimens without smear layer (170, 180). Prati et al. (272) found no difference between stainless-steel K-files and K3, HERO 642, and RaCe NiTi instruments.

Following preparation with FlexMaster and K3, Schäfer & Lohmann (188) and Schäfer & Schlingemann (190) found significantly more debris and smear layer than after manual preparation with K-Flexofiles, although these differences were not significant for the middle and apical thirds of the root canals. RaCe performed better when compared with ProTaper (192). They discovered uninstrumented areas with remaining debris in all areas of the canals irrespective of the preparation technique with the worst results for the apical third. This is in agreement with the results of several earlier studies on post-preparation cleanliness (63, 178–181, 193, 272). These findings underline the limited efficiency of endodontic instruments in cleaning the apical part of the root canal and the importance of additional irrigation as crucial for sufficient desinfection of the canal system. Compared with results of a similar study using ProFile NiTi files, Schäfer & Lohmann (188) found FlexMaster to be superior to K-Flexofiles in terms of debris removal and concluded that different rotary NiTi systems vary in their debris removal efficiency, which is possibly because of differing flute designs. The comparison of previous studies on instruments with and without radial lands (ProFile, Lightspeed, HERO 642) (178–181) confirms the finding that radial lands tend to burnish the cut dentine onto the root canal wall, whereas instruments with positive cutting angles seem to cut and remove the dentine chips.

Nevertheless, it must be concluded from the published studies that the majority of NiTi systems seems unable to completely instrument and clean the root canal walls.

Straightening

Results of selected studies on shaping effects of rotary NiTi systems are presented in Table 5. The vast majority of these studies uniformly describe good or excellent maintenance of curvature even in severely curved root canals. This is confirmed by several investigations of post-operative cross-sections showing good centring ability with only minor deviations from the main axis of the root canal (134, 224, 226, 228, 274, 278, 284, 296–300).

It has been further demonstrated that adequate preparation results can be obtained with NiTi instruments, even by untrained operators and inexperienced dental students (287, 301–303).

Safety aspects

Major concern has been expressed concerning the incidence of instrument fractures during root canal preparation (194). Two modes of fractures can be distinguished: torsional and flexural fractures (304, 305). Flexural fractures may arise from defects in the instrument surface and occur after cyclic fatigue (306). The discerning feature is believed to be the macroscopic appearance of fractured instruments: those with plastic deformation have fractured because of high torsional load while fragments with no obvious signs are thought to have fractured because of fatigue (304).

A summary of factors that may influence instrument separation is presented in Table 6. Anatomical conditions such as radius and angle of root canal curvature, the frequency of use, torque setting and operator experience are among the main factors, while selection of a particular NiTi system, sterilization and rotational speed, when confined to specific limits, seem to be less important (307–338).

Further aspects of working safety such as frequency of apical blockages, perforations, loss of working length or apical extrusion of debris until now have not been evaluated systematically. From the studies described so far it may be concluded that loss of working length and apical blockages in fact do occur in some cases, while the incidence of perforations seems to be negligible. The amount of apically extruded debris has been evaluated in three studies and reported to be not significantly different to hand preparation with Balanced force motion or conventional rotary systems using steel files (13, 153, 154).

Working time

The majority of comparative studies presents some evidence for shorter working times for rotary NiTi preparation when compared with manual instrumentation. NiTi systems using only a small number of instruments, for example ProTaper, completed preparation clearly faster than systems using a large number of instruments (e.g., Lightspeed). It should be noted that reported working times for hand

Table 6. Summary of references investigating the influence of various factors on deformation and separation of NiTi instruments

Author(s)	Year	References	Analyzed factor	Ni–Ti system	Method		Influence	
Silvaggio & Hicks	1997	(307)	Sterilization	ProFile 0.04	1–10 cycles	Torsional test	No	
Pruett et al.	1997	(308)	Canal curvature & rot. speed	Lightspeed	30–60° curvatures,	Simulated canals	Yes	
					2–5 mm radius and 750, 1300, 2000 r.p.m.		Yes	
							No	
Haikel et al.	1998	(309)	NaOCl as irrigant	Different systems	Preparation with/without NaOCl	Torsional test	No	
Mize et al.	1998	(310)	Sterilization	Lightspeed			No	
Mandel et al.	1999	(311)	Operator experience	ProFile 0.04 and 0.06	5 operators	Simulated canals	Yes	Better results in second turn
Baumann & Roth	1999	304	Operator experience	ProFile 0.04	Students vs. practitioners	Simulated canals	No	
Gabel et al.	1999	(312)	Rotational speed	ProFile 0.04	166 vs. 333 r.p.m.	Extracted teeth	Yes	166 r.p.m. with less fractures/distortions
Haikel et al.	1999	(313)	Radius of curvature instrument taper & size	ProFile 0.04 and 0.06, HERO 642, Quantec	5 and 10 mm radius	Fatigue test	Yes	Earlier fracture with low radius
							Yes	Earlier fracture with incr. size
Yared et al.	1999	(314)	Sterilization & simulated clinical use	ProFile 0.06	5 vs. 10 canals/sterilization cycles	Extracted teeth	No	
Dietz et al.	2000	(315)	Rotational speed	ProFile 0.04	150/250/350 r.p.m.		Yes	Less fractures with 150 r.p.m.
Yared et al.	2000	(316)	Sterilization & clinical use	ProFile 0.06			No	
Hilt et al.	2000	(317)	Sterilization	NiTi files	10–40 cycles, 2 autoclaves		No	

Table 6. Continued

Author(s)	Year	References	Analyzed factor	Ni–Ti system	Method		Influence	
Bortnick et al.	2001	(318)	Motor	ProFile 0.04	electric vs. airdriven handpiece	Extracted teeth	No	
Daugherty et al.	2001	(319)	Rotational speed	ProFile 0.04	150 vs. 350 r.p.m.	Extracted teeth	No	
Gambarini	2001	(320)	Motor	ProFile 0.04 and 0.06	high- vs. low-torque	Used instruments	Yes	Low-torque favorable
Gambarini	2001	(321)	Frequency of use	ProFile 0.04 and 0.06	new/used (10 ×) instruments		Yes	Earlier fract. for used instr.I58
Tygesen et al.	2001	(322)	NiTi system	ProFile 0.04		Extracted teeth	No	
				Ni–Ti Pow-R 0.04				
Yared et al.	2001a	(323)	Rotational speed	ProFile 0.06	150/250/350 r.p.m.	Extracted teeth	Yes	150 r.p.m. superior to 350 r.p.m.
	operator experience				3 operators with different experience		Yes	
	torque				20/30/55 Ncm		No	
Yared et al.	2001b	(324)	Motor	ProFile 0.06	high- vs. low-torque	Extracted teeth	No	
Yared et al.	2002	(325)	Rotational speed	GT Rotary	150/250/350 r.p.m.	Extracted teeth	No	
			Torque operator experience		20/30/55 Ncm 3 operators with different experience		No	
							No	
Li et al.	2002	(326)	Rotational speed, handling mode angle of curvature	ProFile 0.04	200/300/400 r.p.m.	Fatigue test	Yes	
							Yes	
Peters & Barbakow	2002	(305)	Number of rotations, torque, force, handling parameters simulated canals vs. teeth	ProFile 0.04	ProFile 0.04/15, 0.04/30, 0.04/45	Fatigue test	Yes	Sign. more rot. to fract. For 0.04/15

Table 6. Continued

Author(s)	Year	References	Analyzed factor	Ni–Ti system	Method		Influence	
Yared & Kulkani	2002	(328)	Motor	ProFile 0.06	Air motor, high- & low- & very-low-torque	Extracted teeth with limited access	Yes	Very low-torque superior
Roland	2002	(329)	Preflaring	ProFile 0.04	Crown-down vs. crown-down+preflaring	Extracted teeth	Yes	Less fract. with preflaring
Zelada et al.	2002	(330)	Rotational speed root canal curvature	ProFile 0.04 & 0.06	150/250/350 r.p.m. $< 30^\circ/>30^\circ$	Extracted teeth	No	
							Yes	All fractures in canals. with $>30^\circ$ curvature
Yared et al.	2003a	(331)	Motor operator experience	ProTaper	high- vs. low-torque 3 operators with different experience	Extracted teeth	No	
Yared et al.	2003b	(332)	Used vs. new instruments	K3		Simulated canals	Yes	Used instruments fracture at lower angles and torque
Martin et al.	2003	(333)	Rotational speed angle & radius of curvature	ProTaper vs. K3	150/250/350 r.p.m. $<30^\circ/>30^\circ$	Extracted teeth	Yes	
							Yes	No influence of radius of curve
O'Hoy et al.	2003	(334)	Cleaning procedures	ProFile	1% NaOCl vs. 1% NaOCl+19% NaCl	Fatigue test	No	Up to 10 cycles without infl.
Berutti et al.	2004	(335)	Preflaring torque	ProTaper	F1, F2, S1 & S2 instruments high vs. low torque	Simulated canals	Yes	
							Yes	
Ankrum et al.	2004	(336)	Type of Ni–Ti instrument	K3, ProTaper & ProFile	severely curved canals (40–75°)	Extracted teeth	No	PT: 6.0% of instr. fractured, PF: 1.7%, K3: 2.1%; diff. not sign.
Fife et al.	2004	(337)	Frequency of use	ProTaper	New/6–8 and 12–16 root canals	Extracted teeth	Yes	Only for S2 and F2
Best et al.	2004	(338)	Deflection angle	ProFile	Varying deflection angles	Fatigue test	Yes	

instruments as well as for NiTi preparation demonstrate large variations, indicating a substantial influence of the operator's attitude and preparation technique.

The Göttingen studies

Studies on rotary NiTi instruments performed with the Göttingen experimental design until now have been performed on the following NiTi systems: Lightspeed, ProFile 0.04, Quantec SC, FlexMaster, HERO 642, ProTaper, RaCe, ENDOflash, NiTiTee, K3, GT Rotary. Some of these systems have been investigated twice. Mean root canal curvature pre-operatively was standardized among the groups and ranged between 25.5° and 28.4°. All root canals were prepared to size #45 or at least to the largest file available if no size #45 instruments were available. A paste-type chelator was used during preparation and irrigation was performed with 2 mL NaOCl after each instrument.

Cleaning efficacy

Throughout the studies no completely cleaned root canals could be found regardless of the NiTi system investigated. Whereas most of the debris was removed different degrees of smear layer were found in all root canals. Cleanliness uniformly decreased from the coronal to the apical third of the root canals, instruments with actively cutting blades showed better cleanliness than files with radial lands.

Straightening

No significant differences were found between the different NiTi systems concerning straightening with exception of more pronounced deviations with Quantec SC, which may be because of the cutting tip of the files. With regard to the experimental set-up (measurement of the movement of the long axis after superimposition of radiographs under a 10-fold magnification) it seems questionable, whether the observed amount of straightening really is of any clinical significance.

Cross-sections

The analysis of the pre- and post-operative cross-sections revealed that most of the root canals showed an oval or round cross-section with most of the circumference prepared. Nevertheless, it must be noted that a noticeable part of the specimens still had unprepared areas in all thirds of the root canal despite preparation to size #45. In addition, it was found that NiTi instruments because of their flexibility had deficiencies in preparation of oval root canals, since it was not possible to direct these flexible instruments into the recesses (137).

Safety

The overall number of procedural incidents such as file fractures, apical blockages, loss of working length or perforations was relatively small when compared with other investigations. Although the operators had been trained before the studies on a limited number of root canals (approximately 20 per system) they should be regarded as inexperienced operators. The maximum number of fractures was five for Lightspeed, but it should be noted that most of these investigations were undertaken with a high-torque motor.

Working time

The results for working time differed widely reflecting operators' experience. Probably, working time is the parameter with the largest inter-individual variations in any preparation technique. Nevertheless, working time was shorter than for manual preparation or most automated systems.

The Cardiff studies

The results of the Cardiff studies are summarized briefly in Table 5. These studies demonstrated an impact of angle and radius of the curvature on preparation outcome. Again, overall there were minor differences between the different NiTi systems with exception of the Quantec SC instruments showing a high number of procedural problems such as perforations, zipping and loss of working length.

The Zürich studies

In extracted maxillary molars, ProTaper, ProFile, GT Rotary, Lightspeed, and FlexMaster prepared root canals without major shaping errors or procedural incidents and similar to NiTi hand instruments used in Balanced force motion (50, 139–142, 292). There were no (50) or few instrument fractures, even though inexperienced operators shaped narrow and curved canals (141, 142). As expected, canal volumes were significantly larger after preparation. However, measured canal volumes after shaping ranged from 1 to about 15 mm^3, and amount therefore to only about 0.1% of the volume used to for irrigation (1–2 mL). Overall, canal transportation was found to be in the range of 100–200 μm, which is in accordance with similar studies (293). A new variable, canal 'thickness', allowed to follow canal profiles and to determine the theoretical depth of insertion of instruments for subsequent root canal filling. It was found that with contemporary instruments and sequences, fine pluggers and spreaders would be introduced to the 5 mm level (141, 142). A further variable, the amount of instrumented radicular wall area, varied among canals, and less so among NiTi instruments used. Overall, 30–40% of the canal surface area remained uninstrumented. In all these experiments, pre-operative root canal geometry was demonstrated to have a greater influence on the preparation result than the preparation techniques themselves (139–142). However, an oscillating instrument produced preparation errors and thinned root dentine significantly compared with the NiTi rotary systems tested earlier (143).

The Münster studies

Some newer NiTi rotary systems were tested in simulated canals in resin blocks as well as in extracted teeth and the results of these studies are briefly summarized in Table 5.

ProTaper, HERO 642, K3, ProFile, FlexMaster, and RaCe respected canal curvature well and were relatively safe to use (186–194). ProTaper showed more transportation to the outer aspect of the curvature. FlexMaster preparations were superior to crowndown preparation using K-Flexofiles in terms of straightening, but root canal walls were significantly better cleaned after manual preparation with K-Flexofiles. There were only minor differences in terms of working time and loss of working length. No completely cleaned canals were found for either technique, although major debris was removed by all systems, with only different degrees of smear layer remaining on the root canal walls. Overall, RaCe performed slightly better than ProTaper (191, 192); K Flexofiles better than K3 (189, 190). Cleanliness decreased from the coronal to the apical third of the canals.

Concerning safety of use some systems as ProFile, K3 and RaCe showed a high incidence of instrument separation. However, as some of these instruments fractured in plastic blocks, care should be take when extrapolating these results to the clinic.

Conclusions

As a conclusion it may be stated, that

- the use of NiTi instruments results in less straightening and better centred preparations of curved root canals,
- the use of NiTi instruments alone does not result in complete cleanliness of the root canal walls,
- cleanliness decreases from the coronal to the apical part of the root canal,
- the use of a paste-type chelator during preparation does not remove the smear layer completely,
- the use of NiTi instruments with active cutting blades is superior to instruments with radial lands in terms of root canal cleanliness,
- when used according to the manufacturers' guidelines NiTi instruments seem to be safe to use,
- the use of instruments with safety tips seems to be preferable with respect to working safety,
- the use of a special motor with constant speed, low torque and torque-control is recommended.

Ultrasonics

The first use of ultrasonics in endodontics was reported by Richman (15). In 1976 Howard Martin developed a device for preparation and cleaning of root canals and named this technique as 'endosonics'. Ultrasonic devices are driven by magnetostriction or piezoelectricity, resulting in oscillation (25–40 kHz) of the inserted file which initiates acoustic microstreaming in the irrigation fluid (339). Initially, it was felt that ultrasonics allowed root canal preparation to be carried out concurrently with activated irrigation, because of cavitation effects (16). However, several studies have demonstrated that acoustic streaming should be regarded the main mode of action (92, 340–344).

Shaping

Results of studies concerning preparation quality of ultrasonic devices in their majority report on unsatisfying results, namely frequent zipping and straightening (13, 54, 57, 63, 88, 117, 241, 247–252, 345–347).

Only few studies have been published reporting good shaping ability of ultrasonic systems (348–350). Several reports have presented pictures of longitudinal grooves in the root dentine following the use of ultrasonically activated files (13, 54, 88, 351) (Fig. 13).

Fig. 13. Root canal wall after preparation with an ultrasonic system showing heavy longitudinal grooves (original magnification × 250). Reprinted by permission from Quintessence.

Cleaning ability

The cleaning and disinfecting capacity of ultrasonics still is subject of controversy (see also other reviews in this issue). Several studies have demonstrated enhanced root canal cleanliness including improved removal of smear layer compared with conventional irrigation techniques (352–361) (Fig. 14); other studies have reported similar results for ultrasonis and conventional preparation/irrigation (83, 84, 88, 89, 169, 251, 255, 362–365), or even superior performance of manual techniques (77, 86).

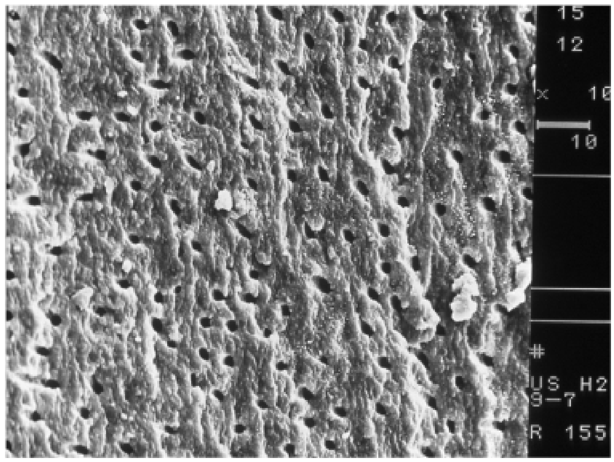

Fig. 14. Root canal wall cleanliness following irrigation with an ultrasonic device and tap water showing good removal of debris and smear layer (original magnification × 1000). Reprinted by permission from Quintessence.

If ultrasonics is used for irrigation purposes care should be taken to introduce the ultrasonic instrument and activate the unit to oscillate the file in the irrigant without touching the root canal walls (360, 361, 366–368).

Working safety

Apical blockages (13, 55, 350), ledging (347), loss of working length (13, 55), a higher risk of perforations (13) and increased amount of apically extruded debris (144, 369) as well as instrument fractures (13, 55, 57, 350, 353, 370) have been described for ultrasonic preparation.

Working time

Time required for ultrasonic preparation has been shown to be shorter (64, 376), longer (13, 55, 346, 357, 366), or equal (253) when compared with hand instrumentation.

In conclusion, the use of an ultrasonic device may be recommended for passive ultrasonic irrigation but not for root canal preparation.

Laser

The first use of lasers in endodontics has been reported by Weichman & Johnson (17). They tried to seal the apical foramen *ex vivo* by means of a CO_2 laser. Since then numerous studies have been undertaken with various types of lasers: Nd : YAG-, KTP-, Er : YAG-, (Ho) : YAG-, XeCl-Excimer-, argon- and free-electron lasers. Laser irradiation has been demonstrated to be able to change or modify the structure of dentine, thereby reducing its permeability (371) and melting or carbonizing its surface. For some lasers the removal of debris and smear layer has been reported (372), but it may be questioned whether it is possible to irradiate the complete lateral canal walls with currently available laser systems emitting the light straight ahead (373). Several investigations have been undertaken to study the sterilization of root canals with different laser types (for a review see Kimura et al. (373)).

In contrast some concern has arisen over the side-effects of lasers such as thermal damage to dental hard tissues resulting in cracks or injury to the surrounding soft tissues such as ankylosis, cemental lysis and bone remodelling (374). Moreover, the shaping ability of lasers in curved root canals seems to be questionable, at least with the current front-emitting probes.

In conclusion, lasers are recommended by some authors for disinfection but at present are not suited for the preparation of root canal systems. The selection of appropriate irradiation parameters is mandatory, but these parameters have not yet been defined for all laser systems. In addition, different tip designs such as flexible and side-emitting probes need to be developed.

NIT

The so-called NIT was developed by Lussi et al. (19). The technique uses a vacuum pump and an electrically driven piston, generating alternating pressure and bubbles in the irrigation solution, inside the root canal. This is expected to enhance the ability of sodium hypochlorite to dissolve organic pulp tissue. Following the cleansing procedure the root canal may be obturated by the vacuum pump with a sealer (375–378).

Studies from the Lussi group demonstrated an equal or even better cleanliness compared with hand instrumentation in root canals of extracted teeth (379–382). In a recent *in vivo* study 22 teeth (18 patients) subjected to extraction because of periodontal destruction were cleansed using the NIT and, following extraction, investigated under the microscope for intra-canal residual tissue. The mean percentage of teeth with tissue remnants and remaining debris in the coronal third of the root canal was shown to be 34.4%, 55.8% in the middle third, and even 76.6% in the apical part (383). Additionally, intra-operative problems as severe pain, underextension and apical extrusion of sealer or breakdown of vacuum have been reported (383, 384) (Fig. 15).

In conclusion, as the NIT system is presently not marketed and long-term observations are missing, it cannot not be regarded as an alternative to mechanical root canal instrumentation.

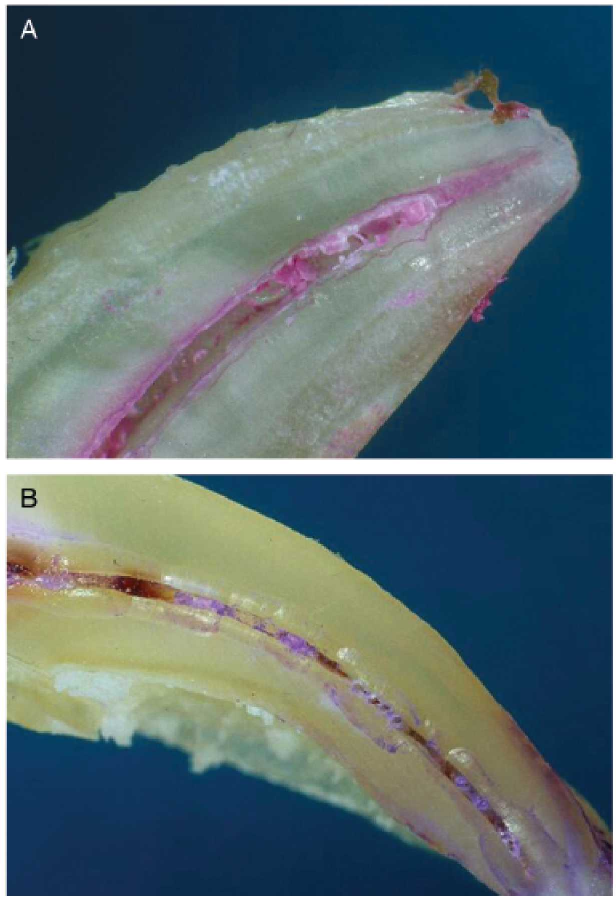

Fig. 15. (A, B) Root canals surface following cleansing with the Non-Instrumental Technique of Lussi demonstrating insufficient cleaning ability with lots of remaining debris and tissue (courtesy of Prof. T. Attin, Göttingen and Prof. A. Lussi, Bern).

Preparation of oval root canals

In the recent literature few data on preparation of oval shaped root canals are available. Such cross-sectional shapes can often be found in the distal root canals of mandibular molars or in mandibular incisors. In an investigation of 180 teeth of all groups Wu et al. (385) detected oval canals in 25% of all sections investigated. According to the criteria used in studies of Wu et al. (385, 386) and Wu & Wesselink (387) only teeth with a bucco-lingual distance at least 1.5 × as long as the mesio-distal distance (internal long to short diameter ratio) are defined as oval. Difficult areas for instrumentation and obturation are the buccal and lingual extensions of these irregular canals (385). Complete preparation with stainless-steel instruments includes a high risk of perforating or significantly weakening the root. On the other hand it seems questionable whether flexible NiTi instruments allow controlled and complete preparation of such extensions. However, specific instrumentation motions such as 'brushing' have been recommended to be used with some instruments (see clinical articles in this issue).

Because of limited efficacy of irrigation in such recesses, debris and smear layer may accumulate and remain on these unprepared root canal walls, decrease the quality of obturation and jeopardize the long-term treatment success.

In a comparative study of preparation of oval root canals with three NiTi systems, preparation with ProFile 0.04 was superior in the apical region compared with Lightspeed and Quantec SC but in all three parts of the root canals no significant differences between the three NiTi systems could be found. The middle and coronal cross-sections were increasingly irregular and frequently showed circular bulges, whereas the buccal and lingual extensions of the oval root canals often remained unprepared (Fig. 16A, B). All three systems performed relatively poorly in these two sections of the root canals probably because of their flexibility frequently not allowing the operator to force them into the lateral extensions. The total amount of non-instrumented canal areas was rather high (19.2%) (137). This is in accordance with the results of a previous investigation by Wu & Wesselink (385), who following preparation of oval canals in mandibular incisors with the Balanced force technique, reported uninstrumented extensions in 65% of the canals. Similarly, three-dimensional rendering of prepared canals demonstrate large uninstrumented areas depending on pre-operative canal shapes (327).

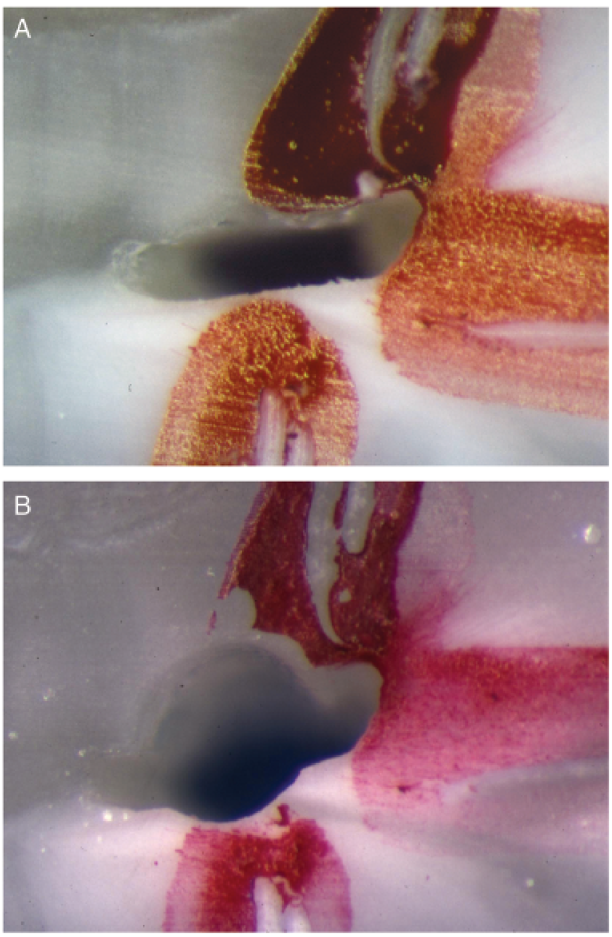

Fig. 16. (A, B) Unprepared buccal and lingual recesses in the distal root of a mandibular molar. The root canal was shaped using NiTi instruments.

Superimposing pre- and post-operative cross-sectional root canal outlines of oval canals Weiger et al. (388) calculated the ratio of prepared to unprepared outlines. Preparation using Hedström files and HERO 642 rotary NiTi preparation showed better results than Lightspeed preparation. Barbizam et al. (389) confirmed these findings in a study on preparation of flattened root canals in mandibular incisors. They reported superior results in terms of root canal cleanliness for the manual crowndown technique using stainless-steel K-files compared with ProFile 0.04 rotary preparation. Another investigation (137) found no significant differences concerning root canal cleanliness between three NiTi systems (Lightspeed, Quantec SC, ProFile 0.04). Cleaning of recesses in oval canals may be enhanced by use of sonic or ultrasonic irrigation techniques, which remove debris but do not affect the smear layer when used with water as the irrigant. Therefore sodium hypochlorite or chelating agents such as EDTA and an adequate irrigation sequence should be selected. When an ultrasonic unit is used for irrigation, the file is best directed towards the extensions and away from danger zones (390).

Apical size of preparation

The desirable final size of apical preparation remains controversial. Two main concepts have been proposed.

The first concept aims at complete circumferential removal of dentine. The traditional rule has been, to prepare at least three sizes beyond the first file that binds at working length. Based on findings that the pre-operative diameter of the apical foramen is approximately 500–680 μm and the diameter of the root canal short of the foramen is on average 300–350 μm (391) apical preparation has been recommended to ISO sizes #25–35 (44, 209, 392–395). Nevertheless, this concept has been questioned fundamentally: as stated earlier, histological studies could demonstrate that 15–30% of the root canal walls remained untouched by instruments following manual preparation even when the recommended instrument sizes were used (396, 397).

Weiger et al. (398) in a laboratory study calculated that enlargement to initial diameter +0.4 mm in molar palatal and distal root canals and +0.3 mm in mesio-buccal, mesio-lingual and disto-buccal root canals of molars would be necessary to achieve complete preparation of the canal circumference in 78% and 72% of the canals, respectively. Preparation to initial diameter+0.6 mm would result in 95% of the cases prepared completely, but included a high risk of perforations.

Several comparative investigations of pre- and post-operative cross-sections of mesio-buccal root canals in curved mandibular molars resulted in 3 to 18 out of 25 specimens with more than 25% of the diameter left unprepared following preparation with different rotary NiTi systems to size #45 (170, 171, 178–183).

The exactness in determination of the ‘first file that binds’ depends on the degree of pre-flaring and the type of instrument used. Following pre-flaring larger instrument sizes can be inserted on working length (difference: one ISO size); larger Lightspeed instruments than K-files could be inserted. When Lightspeed with pre-flaring was compared with K-files without pre-flaring the difference between these techniques increased to three ISO sizes (399).

Wu et al. (400) could detect no difference between K-files and Lightspeed in determination of pre-operative apical diameter. They could demonstrate that in 75% of the root canals the instrument had contact on the canal wall only on one side, in 25% the instrument tip had no contact with the canal wall at all.

Kerekes & Tronstad (401) in histomorphometric studies investigated the smallest file size necessary to prepare a round canal diameter in mesio-buccal root canals of mandibular molars. In 12 out of 19 root canals final preparation sizes of #40–55 were necessary to achieve this goal.

Following preparation with GT Rotary instruments to apical sizes 0.06/20 or 0.06/40 in the first group with smaller apical preparation diameter significantly more debris was found than after extended preparation (402). Similar findings were reported by Peters & Barbakow (403) following preparation with ProFile or Lightspeed instruments showing more effective removal of the smear layer after larger preparation with LS instruments. The technique using the largest final apical file (i.e., Balanced force) produced cleaner apical areas in curved canals than techniques using smaller final apical instruments (stepback, crowndown pressureless) (80). Improved delivery of irrigants is thought to be the main benefit of larger apical preparation sizes (404).

In contrast, in a comparative study of five preparation techniques with the size of the final apical file varying from #25 (stepback technique with stainless-steel files) to #30 (ultrasonics), #35 (stepback, NiTi files; Canal Master U) or #40 (Balanced force) no differences in terms of remaining soft tissue, predentine or debris were detected (405).

The second concept aims to keep the apical diameter small and refers to Schilder’s demand to keep the apical preparation as small as practical (1, 2). This concept for apical preparation includes scouting of the apical third, establishing apical patency with a size #10 instrument passively inserted 1 mm through the foramen, gauging and tuning the apical third and finally finishing the apical third at least to size #20. Corresponding to this technique GT instruments (Dentsply Tulsa Dental, Tulsa, OK, USA) in their original sequence included four instruments for apical finishing all of these with size #20 tips but varying tapers. Similarly, ProTaper Finishing instruments have apical diameters ranging from 0.20 to 0.30 mm.

The influence of final apical preparation size has been examined in two long-term studies on treatment outcome. Whereas Strindberg (162) reported on a poorer prognosis for larger apical preparation, Kerekes & Tronstad (165) found similar results for apical preparation to ISO sizes 20–40 and 45–100. Card et al. (406) *in vivo* could demonstrate a significantly increased reduction of intra-canal bacteria after apical enlargement to larger sizes with NiTi instruments. Based on a review of the literature Friedman recommended larger apical preparation sizes in combination with abundant irrigation and use of a calcium hydroxide dressing (407).

Impact of root canal preparation on the reduction of intra-canal bacteria

While the antimicrobial effect of canal preparation is reviewed in more detail elsewhere in this issue, it is well known that canal shaping and cleaning occur concurrently during mechanical preparation. In fact, in their classical study Byström & Sundqvist (408) using an anaerobic bacteriological technique demonstrated that mechanical enlargement with sterile saline as an irrigant was able to reduce the number of microorganisms in the root canal system significantly from initially 10^2 to more than 10^8 by 100–1000-fold, but could not predictably achieve bacteria-free root canals. Even combinations of mechanical preparation and antibacterial irrigants were not able to eliminate all bacteria from root canals (408–412), demonstrating the limited antibacterial effect of mechanical preparation.

In a clinical study in 23 teeth with apical periodontitis, Ørstavik et al. (413) following stepback preparation and irrigation with sterile saline could yield positive cultures in 14 of the teeth at the end of the first appointment. Following a 1-week medication with calcium hydroxide this number was reduced to eight teeth. At the end of the second appointment bacteria could be detected in two root canals. Although root canals prepared to size #35 or 40 at the end of the first appointment tended to harbor more bacteria than canals prepared to size #45 or more, statistical analysis did not reveal any significance of preparation size on reduction of bacteria.

Yared & Bou Dagher (414) in an *in vivo* investigation in 60 single-rooted teeth with apical periodontitis found no significant difference in terms of the reduction of bacteria following preparation to size #25 or 40, respectively. One percent sodium hypochlorite was used as irrigant. Nevertheless, bacterial counts were reduced significantly in both groups when compared with the initial number of microorganisms.

Coldero et al. (415) instrumented palatal root canals of maxillary molars using sodium hypochlorite (4%) and EDTA as irrigants. There was no significant difference in reduction of intra-canal bacteria following crowndown preparation with GT Rotary to size 0.04/35 and crowndown with GT Rotary to 0.04/20 followed by stepback to 0.04/35. With both techniques the majority of the root canals (15/16 and 13/16, respectively) were rendered bacteria free.

Manual instrumentation using NiTi-Flex instruments to size #40 with 0.02 taper, manual instrumentation using GT Rotary to size 0.12/20 and automated preparation using ProFile 0.06/30 – all techniques used with sterile saline as an irrigant – resulted in 94.2–99.6% reduction of intra-canal bacteria with no statistical difference between the groups (416).

Dalton et al. (417) in a clinical study of 48 teeth with apical periodontitis could find no difference between steel files and NiTi instruments in terms of reduction of bacteria but reported increasing bacterial reduction with increasing instrument size. Nevertheless, it was not possible to achieve bacteria-free root canals predictably. This was confirmed by a similar study on NiTi ProFile 0.04 instruments: Shuping et al. (418) reported on decreasing numbers of intra-canal bacteria with increasing instrumentation sizes. Additional use of 1.25% sodium hypochlorite resulted in 61.9% bacteria-free canals, a calcium-hydroxide dressing increased this figure to 92.5% of the canals. Using ProFile 0.04 and 1% sodium hypochlorite in a clinical study on 40 teeth with apical periodontitis 100% of cuspids and bicuspids and 81.5% of molar canals could be rendered bacteria free after the first appointment.

Continued preparation with Lightspeed instruments to larger sizes resulted in an improvement to 89% bacteria-free canals after this second appointment with the difference between the techniques not being significant (418). Manual preparation using NiTiflex instruments (size #40) in an alternated rotary motions-technique or automated GT Rotary NiTi instruments (0.12/20) with 5% sodium hypochlorite as an irrigant both significantly reduced the number of viable bacteria (60.3–78.4% reduction) but failed to render root canals bacteria free. Additional irrigation with 10% citric acid or 2% chlorhexidine did not result in significant improvement. In the control group instrumentation and irrigation with sterile saline resulted in a 38.3% reduction of bacteria (419). Between manual preparation using K-files or K-Nitiflex files in a stepback technique or K-reamers in a standardized technique no significant differences could be found in reduction of bacteria, although all techniques considerably reduced their number (420).

Rollinson et al. (421) compared the removal of radioactively labeled bacteria with two different rotary NiTi preparation techniques. Preparation with Pow-R instruments to size #50 resulted in less remaining bacteria than preparation with GT Rotary and ProFile to size #35.

In contrast, Ørstavik et al. (422) in a multivariate analysis of the outcome of endodontic treatment in 675 roots in 498 teeth could not find apical extension (i.e. size of final reamer) or point size were among the factors influencing treatment outcome.

In summary, the reduction of intra-canal bacteria will be mainly because of the antibacterial effects of the irrigants (and medications) and only partially because of instrumentation of root canal systems. Mechanical instrumentation will remove a certain amount of infected tissue and dentine from the root canal and facilitate sufficient application of irrigants. Although there seems to be some evidence that larger apical preparation sizes result in the reduction of intra-canal bacteria, the significance of the extent of final apical preparation size remains to be clarified. NiTi instruments are able to enlarge even curved root canals to sizes not routinely attainable with steel files but there is no clear evidence that this automatically results in improved disinfection.

Impact of root canal preparation on treatment outcome

The impact of root canal preparation on treatment outcome recently has been reviewed extensively by Friedman (407) and Kirkevang & Hørsted-Bindslev (423) previously in this journal. In summary, Friedman reported on conflicting results for final apical preparation size and found only one clinical study favouring a certain preparation technique (standardized technique instead of serial preparation) with respect to treatment outcome.

Peters et al. (424) in a retrospective study of 268 clinical cases with 661 roots after a mean observation time of 27.1 ($\pm$9.6) months could not find a difference in treatment outcome between three NiTi preparation techniques (Lightspeed, ProFile 0.04, GT Rotary). It should be noted that only the two first techniques were used with the same obturation technique (lateral condensation with GP and AH 26). Petiette et al. (51) in a 1-year recall study comprising 40 cases reported a significantly better success rate for teeth prepared with NiTi hand files than with stainless-steel K-files by dental students. They conclude that better maintenance of original canal shape led to a better prognosis. However, Ørstavik et al. (422) could not verify an influence of final preparation size on treatment outcome.

Conclusions

Because of the methodological problems described above and limited clinical and scientific evidence conclusions on root canal preparation should be drawn with utmost caution:

- Mechanical preparation of the root canal may result in a significant reduction of bacteria but will not reproducibly leave bacteria-free root canals.
- Mechanical preparation leaves a root canal wall covered with debris and smear layer if not accompanied by abundant irrigation with appropriate solutions.
- Mechanical preparation of the root canal must be assisted and completed by intense disinfection protocols using appropriate irrigants and intracanal medicaments.
- Preparation technique and instruments and final preparation size have to be defined individually for each root canal system.
- The use of NiTi instruments facilitates preparation, especially of curved root canals.

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