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PREPARATION TECHNIQUES IN ROOT CANAL THERAPY

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ABSTRACT

This study reviews critically the literature on preparation techniques in root canal therapy and gives an account of original research which compares the effectiveness, in curved root canals, of four different preparation techniques.

Developments, which address the problem of preparing curved canals specifically, are discussed; these include modification of endodontic hand instruments and the introduction of the step-back technique with and without coronal flaring. Irrigation regimes are reviewed with comment on the chemical nature of irrigants and the means of their delivery into the canal. The biophysical properties of ultrasound are described and a review of endodontic techniques, which incorporate the use of ultrasound, reveals conflict as to the effectiveness of such techniques.

The original investigation compares, by means of a scanning electron microscope evaluation of the canal wall, the effectiveness in curved canals of four preparation techniques: step-back hand instrumentation; hand instrumentation with early access; hand instrumentation with early access and ultrasound; and ultrasonic instrumentation. The most significant findings were that: curved canals, prepared by techniques incorporating ultrasound, were no cleaner than those prepared by hand; and that canal anatomy is an overiding factor in the efficacy of preparation techniques in endodontics.

STATEMENT OF AUTHORSHIP

The work submitted for examination in this thesis is the original work of the candidate alone. The investigation was carried out in the Department of Clinical Dentistry and the SEM Unit of the Westmead Hospital Dental Clinical School. No portion of this work has been submitted by the candidate to any other University in part or in full for the award of any other degree.

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PREFACE

This thesis is presented in two parts.

Part I is a critical review of the literature on preparation techniques in root canal therapy.

Part II is an account of original research, the title of which is:

"A Comparison of Different Techniques for Cleaning Curved Root Canals: A Scanning Electron Microscope Investigation".

The aim of the literature review (Part I) was to assess the current state of knowledge in both the clinical and scientific aspects of the various preparation techniques in root canal therapy. There was always the intent to focus, within this general field, on the particular problem of root canal preparation techniques related to curved canals. The subject of ultrasonics in endodontics was given special attention owing to the recent popularity of techniques employing ultrasound in the preparation of root canals.

The aim of the research (Part II) was to attempt to deal with a problem perceived as a result of the literature review. There was found to be a relative lack of information on the use of ultrasonics in root canal preparation related specifically to curved canals; in particular, information concerning the effects on the walls of curved canals of ultrasonic techniques was found to be wanting.

The conclusions arising from Part I and II are presented separately at the end of each.

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PART I

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LIST OF ABBREVIATIONS

SEM	Scanning Electron Microscope
ISO	International Standards Organisation
FDI	Federation Dentaire International
ADA	American Dental Association
NaOCl	Sodium hypochlorite
H_2O_2	Hydrogen peroxide
EDTA	Ethylene diamine tetra-acetic acid
kHz	Kilohertz
MHz	Megahertz
kV	Kilovolt
mA	Milliamp
cm	Centimetre
mm	Millimetre
µm	Micrometre
BSI	Backscattered imaging
SEI	Secondary electron imaging
Tech	Technique
MB	Mesiobuccal canal of maxillary molar
DB	Distobuccal canal of maxillary molar
MES	Mesial canal of mandibular molar

PART I

REVIEW OF THE LITERATURE

CHAPTER ONE

INTRODUCTION

The need for some manner of root canal preparation prior to root canal filling has long been recognized as an essential step in endodontic treatment. Concepts concerning the role and purpose of this canal preparation, however, have varied at different times in the development of endodontics.

Schilder (1974) defined root canal preparation as cleaning and shaping the root canals. He outlined the objectives as being:

1. "to leave no organic matter in the root canal system that is capable either of supporting bacterial growth itself or of decomposing into tissue-destructive by-products";

2. "to remove from the root canals or destroy, microorganisms that may be present before treatment"; and,

3. "to design and prepare within each root canal that cavity form or shape which encourages the simplest, most effective three-dimensional obturation".

In 1990, these objectives are still relevant but the means of achieving them have varied over time.

Attempts to resolve the problems of cleaning curved canals have led to the introduction of several specialized instrumentation techniques. Additional means of root canal preparation have resulted from the modification of endodontic hand instruments and the introduction of rotary, sonic and ultrasonic instruments. These methods have been the subject of much clinical and scientific investigation.

Preparation of the root canal consists of biomechanical and chemomechanical preparation followed by disinfection. Disinfection is not dealt with specifically in this thesis. Rather, it is the aim of this review to:

1. outline developments in biomechanical preparation (Chapter 2);

2. outline developments in chemomechanical preparation (Chapter 3); and,

3. outline the development of the use of ultrasound in biomechanical and chemomechanical preparation (Chapter 4).

CHAPTER TWO

BIOMECHANICAL PREPARATION

Grossman (1955) was convinced that biomechanical instrumentation was the most important phase of endodontic treatment. He defined biomechanical preparation as the "attainment of free access through the root canal to the apical foramen, the objectives of which are: to cleanse the pulp chamber and root canals; to remove obstructions; to avoid injury to the periapical tissues; to enlarge the canal to receive the maximum amount of intracanal medicament; to smooth and prepare the canal walls to facilitate eventual obturation of the root canal" (p.201).

Schilder (1974) enlarged on the objectives of biomechanical preparation stressing that root canals must be cleaned and shaped. Cleaning includes removal of all organic debris which could possibly serve as a substrate for bacterial growth or as a source of periapical inflammation. Shaping implies development of a unique shape related to length, position and curvature of each individual root and root canal. The shape should also relate to the type of filling material and should be such that a three dimensional obturation of the entire root canal space can be achieved.

Schilder also emphasized that this phase of endodontic treatment was the single most important one. It could be achieved with instruments of specific design (broaches, reamers, files, and certain automated instruments) using irrigating solutions and following biological principles.

2.1 ENDODONTIC INSTRUMENTS

The instruments used in endodontics have been grouped, according to use, by the International Standards Organization (ISO) and the Federation Dentaire International (FDI).[1]

[1] J Am Dent Assoc 99:697, 1979.

Group I: Hand use only - files
reamers
broaches
pluggers
spreaders

Group II: Engine driven - latch type, same design as Group I, but made to fit to a handpiece.

Group III: Engine driven - latch type, drills or reamers, e.g., Gates-Glidden, Peeso.

This section discusses instruments for hand use relevant to root canal preparation (files, reamers and broaches).

2.1.1 **Broaches**

Broaches are available as either smooth or barbed. Smooth broaches have been used to explore the root canal to determine patency, degree of curvature and the location of irregularities in the canal prior to cleaning and shaping. Grossman (1981, p.211) maintained that in using a smooth instrument first, the soft tissue would be pierced or displaced to make room for a rough instrument.

Barbed broaches are used for vital pulp extirpation, to loosen debris in necrotic canals and to remove paper points or cotton pellets from within the canal. They are manufactured from round wire, the smooth surface of which has been notched to form barbs at an angle to the long axis. Barbed broaches should be used with care: forcing the instrument apically beyond the point at which it first binds results in either fracture of the barbs or of the shaft on withdrawal (Ingle & Taintor, 1985, p.176).

2.1.2 Reamers and Files

Reamers and files generally are produced by grinding graduated sizes of round wire into either a square or a triangular configuration. The wire is then twisted anti-clockwise a predetermined number of times to give the instrument the spirals which provide the cutting edges. More recently, the flutes of some reamers and files, e.g., those marketed by Brasseler[2], are produced by grinding instead of twisting.

Reamers are manufactured from a triangular blank which produces a 60° cutting edge. They are made to cut by being tightly inserted into the canal, twisted clockwise one quarter to one half turn to engage the blades, and then withdrawn.

Files were developed in an effort to make a more efficient cutting instrument. Some of the principles of design were changed to achieve this. The triangular blank was replaced with a square blank and twisted more to give a greater number of cutting edges. These files were called "K-type" because they were developed by the Kerr Manufacturing Company[3]. The 90° angle of the square blank did not cut as well as the 60° angle of the reamer but there were more flutes per millimetre on the file, and therefore, more cutting edges. The tighter wind of the spiral decreased the file's flexibility and established a cutting angle that achieved its primary cutting action on withdrawal. The withdrawal action of the file can be effected either in a filing (rasping) action or in a quarter turn or half turn reaming action. Files manufactured from square blanks have a greater cross section which makes them less susceptible to breakage. This is not as significant now that stainless steel instruments, as opposed to carbon steel instruments, are used universally.

In evaluating reamers, Oliet and Sorin (1973) found variation in quality and sharpness of cutting edges, in cross section and in number of flutes. Reamers

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[2] Brasseler USA, Inc., Savannah, GA, USA.

[3] Romulus, MI, U.S.A.

with a triangular cross section were found to cut more efficiently than those with a square cross section but had a higher failure rate, which resulted from deformation or fracture of the blade rather than from wear. They noted that frequent irrigation and debridement was necessary to maintain cutting efficiency. Significant differences in cutting efficiency amongst K-files have also been noted (Newman et al., 1983; Neal et al., 1983).

Reamers and files can be broken by twisting the blades beyond the limits of the metal. Twisting instruments in a clockwise manner after locking can result in unwinding and elongation (Gutierrez et al., 1969). When twisted in a counter-clockwise manner, files are much more brittle and fracture more readily (Chernick et al., 1976).

2.1.3 Standardization of Endodontic Instruments

Following the recommendations of Ingle and Levine (1958), standardized instruments and filling cones were introduced to the endodontic profession in 1959. Instruments are now identified by a number which corresponds to the diameter of the tip D_1, in one hundredths of a mm. This number also identifies the filling point of the same size. The cutting blades of the instruments are 16mm long and the diameter, D_2, at a point 16mm from the tip is uniformly 0.32 mm greater than D_1.

The ADA specification, No. 28, for K-style endodontic files and reamers (1976) established requirements for diameter, length, resistance to fracture, stiffness and resistance to corrosion (Ingle & Taintor, 1985, p.169).

2.1.4 Modification of K-type Files

Some modifications have been made to K-files in attempts to increase their flexibility. Most files in the sizes 10, 15 and 20 have sufficient flexibility because they are small in blank diameter. Increased diameters make the instrument much less flexible. Unitek Manufacturing Company[4] used triangular blanks as for reamers, but introduced increased twisting to gain more flutes per millimetre.

In 1982, the Kerr Manufacturing Company introduced the K-flex file. The cross section of the K-flex file is rhomboidal which creates changes in flexibility and cutting characteristics. The high flutes produce sharp cutting edges from the acute angle of the rhombus while the low flutes provide a reservoir for debris removed by auger action. The thin diamond design allows for more flexibility. When tested for stiffness, the K-flex file was found to be more flexible than four other brands of K-type files (Roth et al., 1983). Not one K-flex file fractured in torque testing. A histological comparison of the canal wall planing ability of K-flex files with conventional K-type files showed no significant difference between the two (Hill & del Rio, 1983). Comparisons were made between K-flex and Unitek files with relation to their effect on canal shape during instrumentation. There were no significant differences between the two (Canales et al., 1984).

The Star Flex-o-file, introduced by Syntex Corporation[5], has a triangular cross section and has been shown to be more flexible than conventional K-files and K-flex files (Krupp et al., 1984). Cimis et al. (1988) compared conventional K-files, K-flex files and Star Flex-o-files with respect to the distance the apical foramen in curved canals was transported, after instrumentation, from its original anatomical position (i.e. apical transportation). They found results were similar regardless of the instrument used.

Since Roane et al. (1985) described the "Balanced Force" concept in endodontic instrumentation, in which they advocated modifying the tip of the file, there has been much interest in this practice. Powell et al. (1986,1988) maintained that modifying the tips to make them parabolic gives greater control over the instrument and the instrument tip tends to ride on the canal wall rather than gouge it. In studies using acrylic blocks, they showed that instrumentation resulted in less deviation from the original canal when files with modified tips

[4] Monrovia, CA, U.S.A.

[5] Valley Forge, PA, U.S.A.

were used. This result was achieved irrespective of the instrumentation technique used. Sabala et al. (1988) found that instrumenting canals in acrylic blocks with modified instruments resulted in less apical transportation and more inner curvature preparation. The modified files maintained the original canal curvature better and more frequently than unmodified files.

2.1.5 Hedstroem Files

Hedstroem files are made by cutting the spiralling flutes into the shaft of a piece of round tapered stainless steel wire in the same manner as woodscrews are made. It is therefore impossible to ream with this instrument. Hedstroem files cut in retraction only. The positive rake of the flute design makes them very efficient as files *per se*. Due to their inherent fragility, Hedstroem files are not to be used with a torquing action.

2.1.6 Unifiles

An additional innovation in file design was made by Burns and McSpadden (Weine 1982, p.259). The flutes of what they termed the "Burns Unifile"[6] are cut in by a machine process. The original wire shaft possesses two machined grooves to produce a double helix design. The flute angle varies from flute to flute allowing for limited action as the instrument is advanced with modest rotation. It therefore possesses the cutting action of both a reamer and a file. It is less efficient in cutting than the Hedstroem file (Ingle & Taintor, 1985, p.175).

2.1.7 SW Endodontic File

Senia and Wildey (1989) have discarded standardized instrument design and introduced an instrument which incorporates 3 new features.

1. It has a non-cutting pilot tip, to limit transportation of the canal.

[6] Ransome & Randolph, Dentsply, Toledo, OH, U.S.A.

2. The cutting segment of the instrument is 2.5 - 4.0 mm instead of 16 mm to give maximal control.

3. The diameter of the instrument's smooth round shaft remains constant and is narrow to increase flexibility.

The aim was to create an instrument which would follow the original curvature of the root canal system more closely and reduce transportation of any portion of the canal. In the initial report (Senia & Wildey, 1989), the new file looks promising but further independent evaluation of the instrument is necessary to confirm the claims made.

2.2 METHODS OF ROOT CANAL PREPARATION

Before 1946, there was little apparent concern for mechanical preparation of the root canal as anything other than a method of obtaining gross access for subsequent canal sterilization. Sterilization was seen as the principal goal of therapy (Ingle, 1961).

At the turn of the century, European endodontics involved amputating devitalized pulps and mummifying the remaining pulp stumps (Levine, 1934). In North America, on the other hand, the removal of the pulp and filling the pulp space with gutta percha was favoured. Emphasis was placed on sterilizing instruments and on developing an aseptic technique. Effective antibacterial agents were used in the canal in preference to strong caustic agents.

As evidenced by the writings of Oldstein (1919), endodontics generally suffered a setback between 1909 and 1919 with the development, in 1909, of Hunter's theory of elective localization and focal infection. This led to wide-scale extraction of pulpally involved and endodontically treated teeth, despite the fact that, at this time, endodontic results were improving with the use of radiographs and effective local anaesthesia.

This indictment of North American dentistry stimulated much research into microbiology and pathology in relation to endodontics. Histological evidence of structural changes following partial pulp removal was published by Davis in the American literature in 1921, but American investigators from 1910 to 1930 were mostly concerned with perfecting the method of pulp removal and treatment of infected root canals.

Early studies of the anatomy of root canals revealed the existence of fine canals with inaccessible branches (Hess, 1921). The problem then arose of what to do about the remnants of pulp tissue in these canals after "pulp removal". Histological studies based on extracted root-filled teeth showed the repair potential of the pulp (Hellner, 1935; Hatton, 1926; Coolidge, 1933). This led to the conclusion that endodontic treatment must be governed by a biological approach to conserve this potential of repair in living tissue within and around the roots of teeth. The belief was held that with an aseptic technique, and use of sterile instruments during treatment, the periapical tissue should heal when freed from infectious material in the root canal. From this point on, active investigation of the bacteriology of endodontics increased. It was stimulated by the search for new drugs which would control infection. A test of root canals for bacterial growth in culture media was advocated prior to filling canals.

Grossman (1955, p.297) pointed out that the bacteriological examination of the root canal as a routine procedure was first suggested as early as 1901 by Onderdonk, but it was Appleton who confirmed, in 1927, the necessity of the practice. Many subsequent studies were interpreted as further evidence in favour of the bacteriologic examination (Appleton, 1932; Grossman, 1936; Buchbinder, 1941). "If the function of root canal therapy is to render the canal and periapical tissues sterile, the only method which can determine whether that objective has been attained is a bacteriological examination" (Appleton, 1932). Theories on medication of root canals were prevalent as the search continued for the ideal drug with which to render root canals sterile.

2.2.1 Mechanical Preparation

Ingle (1961) credits Pucci and Reig with being the first to point out, in 1946, the necessity for meticulous intracanal preparation as a basis for ultimate success in endodontics. In 1953, at a time when antibiotics were gaining favour as intracanal medicaments, Pucci warned that "polyantibiotic therapy supersedes neither biomechanics nor immediate antisepsis of root canals but is an important complement to such treatment" (p.47). This was in accordance with Grossman who, while advocating the use of intracanal antibiotics (a polyantibiotic suspension in particular), never overlooked the importance of biomechanical instrumentation (Grossman, 1951, 1952, 1953).

In 1956, Seidler introduced the concept of the "ideal canal" with reference to its prepared shape, suggesting it "should be perfectly round and tapering and the apical foramen be minute in size" (p.570). Ingle (1961) suggested that this could be achieved by means of reamers to enlarge the apical 3-4 mm of the canal and files to finish the ovoid portion in the coronal two thirds of the canal. The canal could be prepared more rapidly and efficiently and with fewer procedural mishaps if standardized instruments were employed. Green (1958) carried out a microscopic investigation of root canal diameters and stressed the need for correlation between these values and the sizes of the endodontic instruments and filling materials.

From this point on, many studies of the morphology of the prepared canal were undertaken (Haga, 1968; Gutierrez & Garcia, 1968; Vessey, 1969; Schneider, 1971; Davis et al., 1972; Jungman et al., 1975). It became apparent from these that the ideal round preparation was rarely achieved. The use of instruments, either reamers or files, in a reaming action was more likely to produce a round preparation. The filing action of instruments produced a more ovoid preparation (Vessey, 1969; Jungman et al., 1975). Round preparations were also more likely to be prepared in straight, rather than curved canals (Schneider, 1971).

These same studies, designed to look at the morphology of prepared canals, showed them to be poorly debrided. The techniques left a considerable portion of the canal wall untouched by instrumentation (Haga, 1968; Gutierrez & Garcia, 1968; Davis et al., 1972). Walton (1976) found the same when he undertook an extensive histological evaluation of the prepared root canal. These results forced a reconsideration of the clinical criteria for an adequately debrided root canal. Thus, a canal that felt smooth and produced white filings on instrumentation, and/or had been enlarged two to three sizes beyond the first instrument that bound, was not necessarily a well debrided canal.

The introduction of the scanning electron microscope (SEM) as a tool for the evaluation of endodontic techniques (Fromme & Riedal, 1972) led to more research into the efficacy of current instruments and techniques for canal debridement (McComb & Smith, 1975; Lester & Boyde, 1977; Mizrahi et al., 1975; Moodnik et al., 1976; Blackler, 1983). These researchers found that all techniques left considerable debris behind. Some surfaces were smeared and packed with debris while others were untouched by instruments. Lester and Boyde (1977) were able to distinguish more clearly between instrumented and uninstrumented sections of the canal wall by immersing some of the specimens (roots which had been split longitudinally after endodontic preparation) into 5% sodium hypochlorite to render them anorganic. When the canal wall had not been instrumented sufficiently to remove the (unmineralized) predentine, the underlying calcospheritic pattern of the mineralizing front was exposed. Smearing, to a lesser extent, was still evident on the instrumented surfaces of these specimens, occluding the tubules. From this, it was concluded that the smear layer is composed of translocated mineralized dentine deformed under high pressure.

Evidence from SEM studies brought into question again the clinical criteria for assessing completeness of preparation. Enlarging the canal to three sizes beyond the appearance of white filings still left areas untouched and surfaces covered in "sludge" (Moodnik et al., 1976).

2.2.2 Significance of Canal Curvature

The fact that the curved canal poses more problems in debridement than a straight canal has long been recognized. At one point, endodontics was considered contraindicated in teeth with curved canals (Jasper, 1933). Haga (1968) alluded to problems with curved canals, as did Gutierrez and Garcia (1968), who noted that larger instruments were unable to negotiate apical curves and that the resultant canal preparation deviated from the main root canal giving an hour-glass configuration. Schneider (1971) looked specifically at canal preparations in straight and curved canals. In straight canals, the chance of producing a round preparation was 80%, whereas in curved canals it was only 40%.

Weine et al. (1970) described techniques which could be implemented to help negotiate curved canals. These included precurving instruments, using files of size 35 or less at the apex, and establishing intermediate increments. A later study (Weine et al., 1975) reinforced the need to address the problem of the curved canal. By simulating curved canals in acrylic blocks, they demonstrated that the instrumentation techniques used, including precurving of instruments, resulted in hour glass preparations which funnelled to an "elbow", then widened at the apex, producing a tear drop apical foramen; this Weine et. al. (1975) termed the "apical zip". He proposed removing the flutes of enlarging instruments on the outer side of the curve to overcome this problem.

2.2.3 Flared Root Canal Preparations

Schilder (1974) pointed out that all canals curve in one plane or another and, for successful endodontics, the entire root canal system must be cleaned and shaped to receive a three dimensional hermetic filling. He redefined the ideal preparation as a continuously tapering funnel from apex to chamber which should relate to the original length, position and curvature of each individual root and root canal. To achieve this, serial filing and reaming with recapitulation was recommended in preference to sequential placement of all instruments to the apical end of the preparation. Increasing stiffness of larger instruments severely restricts their placement around curves. In advocating the use of Gates-Glidden drills in the coronal third, Schilder was one of the first authors to stress the need to flare root canal preparations. This enhances the access to the apical third and also the vertical condensation of gutta percha.

Histological evaluation of serial instrumentation was carried out by Coffae and Brilliant (1974) and Walton (1976). In comparing serial and standard instrumentation, Coffae and Brilliant (1974) found the former much more effective in removal of tissue from the canal when cross sections 1 mm, 3 mm and 5 mm from the apex were examined under the light microscope. Walton (1976) examined both horizontal and longitudinal sections under the light microscope and quantitated the percentage of walls planed in each. Three techniques were evaluated in straight and curved canals. All techniques were more effective in straight canals while the step-back procedure was the most effective in curved canals.

Mullaney (1979) described three techniques for the instrumentation of finely curved canals: a classic "step-back" (interchangeable with serial or telescopic) preparation, the Ohio State technique and the Southern California technique. The step-back technique consists of enlarging the apex to a size 25 file and subsequently stepping back in 1 mm increments. Recapitulation, i.e., the reapplication of smaller instruments previously used, is an essential part of this procedure. The Ohio State and Southern California techniques aim to enlarge the apex to size 40. To achieve this, the Ohio technique involves enlarging the coronal segment with the Gates-Glidden drills after the apex has been enlarged to size 25. Larger instruments are then placed at working length. The third technique involves modifying the access and applying mesial pressure on the instruments, which tends to straighten the curvature of the original canal. In an evaluation of these techniques, plus two traditional ones, Mullaney concluded that the step-back technique was the most effective instrumentation procedure with reference to canal shape and to the operator's ability to follow the original curvature of the canal.

Bolanos and Jensen (1980) evaluated the serial and non-serial instrumentation techniques in the buccal canals of maxillary molars using the SEM. They concluded that serial preparation was a better technique of instrumentation, as it provided a cleaner canal, although both techniques resulted in a canal wall with a smeared layer of debris. A study by Allison et al. (1979) reinforced the trend to widely flared canal preparations; it indicated that the flared canal allowed deeper spreader penetration during the lateral condensation of gutta percha when compared with traditional instrumentation. The deeper the spreader penetration the better was the apical seal, as illustrated by isotope leakage tests. After the publication of these articles, there followed in the endodontic literature of the 1980's numerous personalized instrumentation techniques designed to clean and shape curved root canals.

2.2.4 Early Access Techniques

Goerig et al. (1982) recommended a technique whereby "radicular access" was gained with the use of Hedstroem files and Gates-Glidden drills in the coronal half of the canal. Apical preparation then followed using K-files in a step-back manner. This became known as one of the first "early access" techniques. Fava (1983) described what he termed the "double flared technique", the aim of which was to provide early flaring of the coronal two thirds of the canal and thereby decrease the potential for forcing material through the foramen. This was achieved by placing sequentially larger files at greater depths so the apical preparation was stepped down (rather than back). This was continued until the appropriate file size reached working length. The "crown down pressureless technique" described and evaluated by Morgan and Montgomery (1984) is a similar concept with early access obtained with K-files and Gates-Glidden drills and the apical preparation stepped down. This technique was compared with that of circumferential filing with precurved instruments by injecting the root canal system with impression material, histologically "clearing" the teeth and evaluating the impressions. The "crown down pressureless technique" received, overall, the best ratings although it was a fairly subjective assessment.

Early access with canal orifice enlargement was found to avoid restriction of the exploratory, as well as of the working instrument (Leeb, 1983). The exploratory instrument is less likely to bind coronal to the apex if the coronal two thirds of the canal is straightened. This enables the size of the apical foramen to be more accurately determined.

2.2.5 Precautions in Flaring Root Canal Preparations

All the techniques mentioned above aim to create a continuously tapering funnel in canal preparation by flaring of the coronal segment. This is either intentional, through additional instrumentation with K-files, Hedstroem files and automated instruments; or, it may be less deliberate, through constant recapitulation of finer instruments into the apical part of the canal. In 1980, Abou-Rass et al. first drew attention to the hazards of removing too much tooth structure from the coronal segment of the canal. This thinning of the dentine back to the cementum (stripping) can occur if care is not taken to avoid over-zealous instrumentation in susceptible areas. They described an anti-curvature method of filing root canals towards the area of greatest bulk of tooth structure and away from the furcation surface in molar roots. Kessler et al. (1983) studied 60 mandibular molars comparing the relative risk of molar root perforations using different instrumentation techniques. Hand instrumentation in an anti-curvature manner offered the greatest protection against stripping perforations as compared to other flaring techniques. The amount of dentine left in danger zones after standard instrumentation was similar to that left after anti-curvature filing. The level of greatest danger of perforation in mesial roots was the furcation surface approximately 2.8 mm below the bifurcation. They suggested that the use of Gates-Glidden drills at this level, in order to gain additional flaring, could be hazardous owing to the difficulty of directing them away from the furcation surface without the risk of drill fracture. A study by Lim and Webber (1985) using extracted teeth with curved canals substantiated these findings. Circumferential filing, despite a step-back technique, resulted in "zip formation" at the apex and considerable thinning of dentine in the inner curve.

Recommendations put forward were to use anti-curvature filing and to perform some coronal enlargement before preparing the apical segment.

A study by Mayne in 1988 gave credence to the warnings of Abou-Rass et al. (1980) and Kessler et al. (1983). Twenty-six molars were instrumented by various techniques including standardized, step-back, early access, ultrasonic, ultrasonic/step-back, and Roane balanced force (see below, p.18). Horizontal sections were made of the roots after preparation and all sections were examined by low magnification light microscopy. Buccal roots of upper molars and mesial roots of lower molars had the thinnest remaining walls. The furcation surfaces 2-4 mm apical to the bifurcation or trifurcation were the thinnest. No attempt was made to relate minimal wall thickness either to operator or technique, however, it is of some concern that more than one half the teeth instrumented had at least one root with a minimal wall thickness of 0.5 mm or less.

2.2.6 The Roane Technique

A very different approach to instrumentation of curved canals was advocated by Roane et al.(1985). They described what they termed the "balanced force" concept of endodontic instrumentation which, they stated, prepared the canal according to its original size and not to the degree of curvature. Files with a triangular cross-section were placed in the canal using clockwise rotation and light inward pressure; cutting was accomplished using counter-clockwise rotation and inward pressure to match the file's strength. They found that better instrument control was achieved if the instruments were modified to make the tip parabolic.

Southard et al.(1987) evaluated the Roane technique in extracted molar teeth and found that it was possible to accomplish effective instrumentation of curved canals using straight instruments. Canals were prepared to file size 40 apically and the patency, original shape and position of the apical foramen were all maintained. Powell et al.(1986, 1988), using simulated canals in acrylic blocks, examined the influence of the modified instruments on canal preparation. They found that irrespective of instrumentation technique, the use of the modified instrument resulted in three desirable features: there was better control of canal preparation size; preparations were smoother; and, the original canal shape was better maintained. Sabala et al.(1988) found that, particularly when the Roane technique was employed, the differences between canal preparations using the modified instrument and those using a non-modified instrument were significant. Their findings were similar to those of Powell et al. (1986,1988) in that the use of the modified tip resulted in the same three desirable features: original canal curvature was better maintained; preparations were smoother; and the size of preparation was better controlled.

2.3 ENGINE DRIVEN ENDODONTIC INSTRUMENTS

The ISO Group I instruments (instruments for hand use only) have been discussed in Section 2.1.1. ISO Groups II and III are discussed below.

2.3.1 **ISO Group II Endodontic Instruments** (two part shaft and operative head)

Included in Group II are endodontic instruments which have shafts designed for use in straight or contra-angle handpieces or specially designed endodontic contra-angle handpieces. The operative head is identical with the files, reamers and broaches of Group I or with specially designed root canal instruments.

2.3.2 **Endodontic Handpieces**

Contra-angle endodontic hand pieces have been designed specifically, to deliver three different movements to endodontic files:

a) a reciprocating/quarter-turn action;
b) a vertical vibratory motion; and
c) a combination of quarter turn and a vertical movement.

The Giromatic[7] and the Union Broach Endo angle[8] handpieces deliver a quarter turn action while the Societé Endo Technic handpiece (canal finder system)[9] imparts only vertical vibratory motion to the file. Handpieces which deliver a vertical and a quarter turn action to the file are the W & H[10], the Endomatic[11], the Endolift[12] and the Racer[13] handpieces.

Of the handpieces mentioned, the Giromatic is the most widely used. It delivers a quarter turn motion 3000 times per min and accepts only latch type instruments. It was introduced in 1964 for use with a single barbed broach labelled "xxxxfine". Later, three other sizes were added and, in 1970, engine operated Hedstroem files were introduced. Many authors have pointed out the advantages of the Giromatic handpiece (Frank, 1967; Fromme & Reidal, 1972; Harty & Stock, 1974). Its widespread use was encouraged by its ease of manipulation and the flexibility of the instruments used with it. Subsequent reports have suggested that its ease of manipulation is deceptive with respect to the ability of the instrument to debride efficiently and follow the original path of the root canal. Mizrahi et al. (1975) found that canals prepared with Giromatic files (a Hedstroem file with a blunter tip and fewer cutting spirals) were cleaner than those prepared with Giromatic broaches. The barbs of the broaches flattened out and the shafts often broke. Neither technique was found to be as effective as hand instrumentation. Klayman and Brilliant (1975) showed that serial instrumentation was significantly more effective than the Giromatic technique in removing tissue debris from curved root canals. Jungman et al. (1975) pointed out that while neither hand instrumentation nor use of the

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[7] Micro-Mega, Besancon, France

[8] Union Broach, Long Island City, N.Y., U.S.A.

[9] Societé Endo Technic, Marseille, France.

[10] W & H Dentalwork, Buermoos

[11] Maillefer, France

[12] Kerr, Romulus, MI, U.S.A.

[13] Racer-Cardex, Klagenfurt, Austria

Giromatic technique produced the desired "round preparation" in curved canals, the most irregular canals were produced by the Giromatic technique.

O'Connell and Brayton (1975) graded the preparations of straight and curved canals with respect to shape, morphological aberrations, surface smoothness and apical preparation. The overall results for hand instrumentation were excellent. The Giromatic canal preparations were marginally better than those prepared with the W & H handpiece which produced the least satisfactory results. Weine et al. (1976) found hand instrumentation of canals simulated in acrylic to be superior to preparation with the Giromatic and the W & H handpieces. Both the automated handpieces created severe alteration in canal shape. Despite the results, the Giromatic handpiece had a "good feel" while the W & H handpiece had a poor feel. In an *in vivo* study comparing Giromatic with hand instrumentation, Turek and Langeland (1982) were unable to enlarge curved canals with the Giromatic broaches or files without ledging and straightening the canal and losing working length. Lehman and Gerstein (1982) evaluated three automated handpieces and compared them with serial instrumentation. They found that the Giromatic was more efficient than the Endo angle and the Endolift techniques, but that hand instrumentation was the fastest method, packed the least debris and created the least "zipping" in both simulated curved canals and extracted teeth.

2.3.3 Files Specifically Designed For Use In Endodontic Handpieces

Felt et al. (1982) found reamers in a Giromatic handpiece to be more efficient than files, and smaller instruments more efficient than large ones. This study, and others mentioned above, led to the belief that a fundamental problem with automated techniques was that the cutting blades of reamers and files were not specifically designed for use with powered instruments. The Dynatrak file[14] was the first instrument specifically designed for use in the reciprocating handpiece. It is a variation of the Unifile, has a non-cutting pilot tip, and was developed by McSpadden (Ingle & Taintor, 1985). Ingle and Taintor (1985, p.178) reported

[14] Ransome and Randolph, Dentsply, Toledo, OH, U.S.A.

that Massoth in 1982 compared the Dynatrak system with hand instrumentation and found that hand instrumentation resulted in a more consistent shape of the prepared canal, less build-up of dentinal debris apically, and fewer untouched canal walls. Rispi files[15] are barbed instruments designed for use with the Giromatic handpiece and, when evaluated by Tronstad and Niemczyk (1986), were found to be very efficient and remarkably safe in straight and curved simulated canals. Efficiency of the Giromatic handpiece increased three-fold when Rispi files were used and complications were far fewer than when the original barbed broaches and files were used. Spyropoulos et al. (1987) evaluated the effect of Giromatic files (Dynatrak and Giro Trio-cut[16]) on the preparation shape of severely curved canals. In comparing hand and Giromatic files of the same design, they found no significant differences in either instrumentation time or the number of procedural errors. Giromatic files produced wider apical preparations while hand instrumentation produced a more flared preparation. The Societé Endo Technic handpiece uses specially designed modified K-files as well as Hedstroem files in small sizes and moves them up and down only. Studies have shown that this system does not straighten curved canals during preparation (Goldman, 1987; Tronstad & Niemczyk, 1986).

2.3.4 **Sonic Endodontic Instruments**

The sonic and ultrasonic endodontic instruments are without ISO classification as yet. Ultrasonics in endodontics is covered in Section 4.3: the sonic instruments are discussed below.

In 1985, Tronstad et al. reported on the effectiveness of a sonic vibratory endodontic instrument - the Endostar 5[17]. The handpiece is connected to the high speed air line of a dental unit and operates at 6500 Hz. When activated, the attached K- file vibrates in a whirling motion, and continuous irrigation is delivered through the handpiece. Results in simulated canals show curvature is

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[15] Medidenta International Inc., Woodside, N.Y., U.S.A.

[16] Medidenta International Inc., Woodside, N.Y., U.S.A.

[17] Syntex Dental Products, Valley Forge, PA, U.S.A.

well maintained with no ledging. The time taken was found to be the same as for hand instrumentation but with much less operator fatigue. In a further study, Tronstad et al. (1986) evaluated six different automated devices used for root canal preparation. The three most efficient devices were the Giromatic Rispi[18], the Canal Finder System and the Micro-Mega 3000 Sonic System[19]. Only the last was without complications such as fractured instruments. The Dynatrak system and the Cavi-endo[20], a device energized by an ultrasonic unit, failed to maintain working length in all instances and files fractured in severely curved canals. Working length was maintained with the Endostar but some instruments fractured in severely curved canals. An important finding was the influence of the root canal instruments on the efficacy and safety of the devices. Goldberg et al. (1988) found no significant difference between hand and sonic instrumentation when these techniques were evaluated for ability to debride canals of extracted single rooted teeth. Bolanos et al. (1988) evaluated the Micro-Mega 3000 sonic unit with Rispisonic[21] and Shaper[22] files using extracted human molars; they compared these techniques with hand instrumentation (K files) and Giromatic instrumentation (Rispi files). The Micro-Mega 3000 with Rispisonic files produced the cleanest canals when canals were straight whereas, in the apical section of curved canals, Shaper files produced the best result. In almost all instances, the Micro-Mega 3000 sonic system performed better than hand instrumentation. Haikel and Allemann (1988) found that canal shape produced by hand instrumentation was superior to that produced using the Sonic Air 3000 with Rispisonic and Shaper files. Hand instrumentation produced a canal that was clean for the entire length whereas the sonic air methods produced a very clean canal in the coronal two thirds.

The results of many of these studies are conflicting. When interpreting the results, it must be taken into account which particular feature of the system or

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[18] Micro-Mega, Geneva, Switzerland

[19] Micro-Mega, Geneva, Switzerland

[20] Caulk, Melford, DE, U.S.A.

[21] Micro-Mega, Geneva, Switzerland

[22] Micro-Mega, Geneva, Switzerland

instrument has been assessed. The instrumentation used in those techniques producing the cleanest canal may not necessarily have followed the curvature of the canal as accurately as others. However, from the literature, it would be reasonable to conclude that there are now available automated endodontic instruments which are efficient and safe.

2.3.5 ISO Group III endodontic instruments, engine driven

ISO Group III endodontic instruments (engine-driven) are a one-part shaft and operative head. Included are B-1, G-type (Gates-Glidden[23]) P-type (Peeso[24]), A-type, D-type, M-type, and T-type reamers. These are used in a full rotary handpiece. They are generally used to funnel out orifices for easier access, to widen as much as two thirds of the canal, or to prepare post space for final restoration of the tooth. The two most popular instruments of this kind are the Gates-Glidden drills and the Peeso reamers (drills).

Gates-Glidden drills are an integral part of the early access instrumentation techniques (see p.15). They are designed to have a weak spot in the part of the shaft closest to the handpiece so that the separated instrument can be easily removed from the canal. Both the Gates-Glidden and the Peeso drills have been recommended for orifice opening in molars (Abou-Rass & Jastrab, 1982; Leeb, 1983). Abou-Rass and Jastrab found that the combination of hand instrumentation and the Peeso or Gates-Glidden drill produced a superior canal preparation, saved time and reduced the potential for error. They found the Peeso size 1 or the Gates-Glidden sizes 2 and 3 satisfactory for this purpose. They stated that the removal of the cervical constriction of the canal is important in preparing the mid sections. Leeb (1983), in accordance with this view, stated that if the orifice is not enlarged (in mesial canals of mandibular molars, for example), doing so with a file will cause the file to flex and remove dentine from the distal wall. This results in a non-tapered hour glass preparation with a constriction at the cervical level. He concluded that the Peeso drill was more

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[23] FKG Co., La Chaux-de-Fonds, Switzerland.

[24] FKG Co., La Chaux-de-Fonds, Switzerland.

efficient for this purpose than the Gates-Glidden. Both Peeso and Gates-Glidden drills should be "safe ended" so they will not perforate. Mention has already been made of the hazards of over-zealous coronal flaring (Mayne, 1988).

2.4 SUMMARY

It is evident that in many cases the guidelines for the completeness of canal preparation has varied between researchers. However, there is universal agreement that these clinically-usable criteria are inadequate as an indication of the degree of cleanliness and smoothness of the root canal walls.

Many researchers report evidence of residual pulp and dentine debris in light and electron microscopic studies: regions of the prepared canal appear to remain untouched by instruments during canal preparation.

The problem of thoroughly debriding curved canals is recognized and many techniques and instrument modifications have been designed to address this problem. Step-back instrumentation was introduced and coronal flaring of the canal advocated. Many specialized techniques incorporated variations of these two processes, however, they were not without risk. Means of avoiding over-zealous flaring have been outlined, and a technique designed for use in curved canals which avoids coronal flaring has been described.

Engine driven endodontic instruments have been used alone or in combination with hand instruments. Techniques involving the Giromatic handpiece are among the most widely used, but they are no more effective than hand instrumentation techniques in debriding and maintaining the shape of the canal. Reports on sonic techniques are conflicting: it is possible that sonic instrumentation results in canals comparable in shape and cleanliness to those prepared by hand. In both Giromatic and sonic techniques, the design of the file has a significant effect on the performance of the system in general.

Flaring of the coronal section of the canal is still the most acceptable approach to instrumentation in curved canals. The use of rotary instruments, either Gates-Glidden drills or Peezo reamers, is incorporated into most of the flared and early access techniques of root canal preparation.

CHAPTER THREE

CHEMOMECHANICAL PREPARATION

The term chemomechanical preparation has been applied to the use of certain chemical agents, in combination with endodontic instruments, to clean and shape the root canal (Schilder, 1974). Discussed in this section are the relevance to root canal preparation of irrigation, the irrigating solutions available and the various chemical aids used to facilitate penetration and enlargement of narrow and occluded canals.

Thorough debridement of the root canal system is recognized as being essential for successful long term root canal therapy. Although preliminary debridement is accomplished with hand instruments, these instruments alone are not able to remove all the tissue remnants in the pulp chamber and canals (Baker, et al.1975). Mechanical preparation in conjunction with chemical debridement will result in a cleaner canal with a generally reduced bacterial population than when mechanical preparation alone is performed (Auerbach, 1953; Nicholls, 1962; Ingle & Zeldow, 1958; Stewart, 1955; Byström & Sundqvist, 1981, 1983, 1985).

Grossman (1943) emphasized that it is an axiomatic principle of surgery that before a wound is ready for chemotherapy, all necrotic material and debris must be removed. This principle, he stated, should not be overlooked in endodontics. Masterton (1965) likewise stressed the analogy between endodontics and general surgery.

Luebke (1967) listed the objectives of irrigation as: removal of hard tissue debris accumulating during preparation of the access cavity; removal of soft tissue remnants and necrotic organic material; physical washing out of bacteria and their products; and the chemical destruction of those organisms susceptible to drug action. He defined the ideal irrigating solution as a non-viscous, non-irritating germicidal solution with detergent qualities and the ability to dissolve necrotic tissue.

Weine (1982, p.267) stated that instrumentation must always be carried out in a wet environment to avoid packing of dentinal shavings near the apex. Fracture of endodontic instruments is minimized by a well lubricated canal.

Ingle and Taintor (1985, p.180) summarized the goals of irrigation as tissue dissolution, antibacterial action and lubrication. A suitable irrigant should possess these properties and should also be non-toxic to periapical tissues. The ability of an irrigant to soften dentine by demineralization has also been considered desirable.

3.1 HISTORICAL ASPECTS

Various substances including water and saline have been used over the years to aid in the cleaning of root canals. Historical reviews (Grossman & Meiman, 1941; Masterton, 1965) mention acids, proteolytic enzymes and alkaline solutions.

Acids such as 30% hydrochloric acid and 50% sulphuric acid were used as late as the 1940's with little understanding of the hazards these agents posed for the periradicular tissues. The acids dissolved the inorganic structure of dentine, and the remaining organic matrix offered far less resistance to instrumentation. Proteolytic enzymes were utilized in the 1930's and 1940's for their supposed tissue solvency property. Those used included enzymol, galactonic lactone, papain, tendra, streptokinase, and streptodornase. Alkaline solutions used as endodontic irrigants included sodium dioxide, sodium hydroxide, potassium hydroxide, urea, and sodium hypochlorite. Grossman and Meiman (1941) compared the tissue solvent ability of most of the above mentioned agents and found chlorinated soda solution (double strength USP) to be the most effective pulp tissue solvent. It was the only chemical solution investigated that dissolved pulp tissue in less than 2 hrs, occasionally effecting complete solution in less than 20 mins. Chlorinated soda is an aqueous solution made up of sodium hypochlorite (NaOCl) and sodium chloride containing at least 5% available chlorine; its use as an endodontic irrigant was first recommended by Walker in 1936.

In 1943, Grossman introduced the concept of using NaOCl as an irrigant in conjunction with another oxidizing agent. He recommended that a solution of 3% hydrogen peroxide be alternated with a solution of 5.25% NaOCl so that the effervescence from the chemical reaction would help to force debris toward the pulp chamber. The chemical reaction is as follows.

$$NaOCl + H_2O_2 \rightarrow NaCl + H_2O + O_2$$

3.2 SODIUM HYPOCHLORITE

Sodium hypochlorite is one of the most popular irrigating solutions (Ingle & Taintor, 1985, p.180). Research has revealed much of its chemical and clinical properties. It is a strongly bactericidal and cytolytic chlorine compound.

3.2.1 Antimicrobial Action

Sodium hypochlorite is a broad spectrum antimicrobial agent effective against bacteria, bacteriophages, spores, yeasts and viruses (Auerbach, 1953; Friberg & Hammarström, 1955; Shih et al., 1970; Spangberg et al., 1973; Harrison & Hand, 1981; Foley et al., 1983). It is evident from the literature that the antimicrobial effect depends on several factors: concentration, pH, time, temperature and strain of microorganism. The bactericidal and viricidal action increases with falling pH, higher temperatures and rising concentration of the solution.

According to Friberg and Hammarström (1955), a thousandfold reduction of the most resistant phages required about 2.5 ppm free available chlorine at 1 min exposure, pH 7.8 and 6°C. At 20°C, the bactericidal and viricidal effects were greater at the same exposure time. Cunningham and Joseph (1980) showed that 2.6% NaOCl was a more effective bactericidal agent when used at body temperature rather than at room temperature. Shih et al. (1970) evaluated the bactericidal efficiency of Clorox[25] and, in a laboratory tube dilution study, found a dilution of 1:1,000 (0.00525% NaOCl) to be a powerful germicide. However, evaluation using a simulated clinical irrigating procedure showed that only 5.25% NaOCl (5 ml introduced over a 3 min period) had a one hundred per cent sterilizing effect in canals inoculated with *Streptococcus faecalis* and *Staphylococcus aureus*. Harrison and Hand (1981) showed that dilution of 5.25% NaOCl, as well as the presence of organic matter, significantly decreased the antibacterial effect of NaOCl *in vitro*. This was in contrast to Spangberg et al. (1973), who had recommended a 1% solution of NaOCl, pH 8.9, as sufficient to kill all bacterial strains present in necrotic pulps. The exposure time necessary was 5 - 10 mins. A clinical study by Bystrom and Sundqvist (1985) reinforced Spangberg's claims by showing that there was no significant difference in the antibacterial effect when irrigating with 0.5% NaOCl or 5% NaOCl (both at pH 9).

3.2.2 Solvent Action

Grossman and Meiman (1941) evaluated 9 different agents recommended at the time for root canal irrigation. Of these, only chlorinated soda solution (5% available chlorine) proved to be an effective solvent of pulp tissue. Like its antibacterial property, the tissue dissolving property of NaOCl is a function of pH, concentration, temperature and time. It is also dependent on the proportion of solution to substrate, on the type of tissue to be dissolved, and on the extent to which the solution has been flushed, mechanically agitated or ultrasonically activated.

3.2.2.1 pH

Sodium hypochlorite exerts its strongest oxidizing action on vital tissues in nearly neutral solutions (pH 7.4) (Dychdala, 1977). However, this pH range

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[25] A product of Clorox Company, Oakland, CA, U.S.A

contains	Sodium Hypochlorite	- 5.25%
	Sodium carbonate	- 0.20%
	Sodium chloride	- 4.0%
	Free sodium hydroxide	- 0.005-0.015%

causes an unstable and markedly cytotoxic solution. Most of the lytic action occurs in the first few minutes when the effective oxidizing components (undissociated HOCl and OCl^- ions) are highly active. Despite these observations, Mentz (1982) reports that Lamers et al. in 1972 found highly alkaline solutions (pH 11 - 12.5) to cause the most rapid dissolution of necrotic substrate.

3.2.2.2 Temperature

Cunningham and Balekjian (1980) have shown that 5.25% and 2.6% NaOCl are equally effective as tissue solvents at 37°C. At room temperature (21°C), however, the 2.6% solution was less effective. Abou-Rass and Oglesby (1981) found the solvent ability of NaOCl was greatest when heated to 140°F compared to room temperature (73.2°F), but concluded that regardless of temperature, 5.25% NaOCl was a better tissue solvent than 2.6% NaOCl.

3.2.2.3 Concentration

A 5.25% solution of NaOCl is an effective solvent of vital, necrotic and fixed tissue (Grossman & Meiman, 1941; Rosenfeld et al., 1978; Hand et al., 1978; Thé, 1979; Abou-Rass & Oglesby, 1981). The effect of diluting a 5.25% solution is much debated in the literature.

Hand et al. (1978) dissolved pieces of necrotic tissue in NaOCl and observed that dilution of 5.25% solution greatly reduced tissue dissolution. They stated that the surface area of the tissue exposed to the test solution was also of importance but did not prove this. Trepagnier et al. (1977) made a quantitative evaluation of canal irrigants by analyzing the hydroxyproline content of the solution resulting after irrigation. There was a significant difference between the 5% and the 0.5% solutions. However, dilution with an equal part of water did not significantly decrease the effectiveness of the 5% solution. They concluded that NaOCl was a powerful tissue solvent whose action started immediately and continued for at least 1 hr.

Thé (1979) studied the ability of NaOCl to dissolve necrotic tissue and fixed necrotic tissue. Necrotic tissue fragments were fixed using either 20% parachlorophenol or 25% formalin in 80% ethanol. These fixed and necrotic tissue fragments from the rat abdominal wall were then brought into contact with 1%, 2% and 3% solutions of NaOCl. A concentration of 3% NaOCl dissolved almost all necrotic tissue within 30 mins. The solvent action of the 2% and 3% NaOCl solutions was dependent on contact time and the ratio between the amount of tissue and the quantity of solution. Fixed tissues were more difficult to dissolve. Gordon et al. (1981) used vital and necrotic bovine pulp tissue to demonstrate the solvent effects of 1%, 3% and 5% NaOCl over periods of time from 2 - 10 mins. The 3% and 5% solutions were seen to be equally effective on vital tissue after only 2 mins of exposure and the 1%, 3% and 5% solutions were equally effective after 5 mins on necrotic tissue. Koskinen et al. (1980) dissolved small pieces of bovine pulp tissue and confirmed the efficacy of 5% and 2.5%, but not 0.5% NaOCl. The importance of good contact between tissue and irrigant was mentioned.

Senia et al. (1971) evaluated the solvent effect of 5.25% NaOCl on pulp tissue in the mesial canals of extracted human mandibular molars. At the 1 mm and 3 mm levels from the apex, there was no difference between NaOCl and saline in their ability to remove organic tissue. At the 5 mm level, the NaOCl was much more effective. They concluded that to get maximal tissue dissolving ability from NaOCl there must be maximal surface contact with the tissue being treated, a large volume of the solution, and adequate exchange with fresh solution. All three objectives are difficult to realize in the narrow confines of the apical 3 mm of fine canals. Rosenfeld et al. (1978), while demonstrating that 5.25% NaOCl exerted a non-specific surface solvent action on intact vital pulp tissue (of human premolars), also noted that this effect was limited by a small lumen and was mostly observed in the middle and occlusal thirds. Rubin et al. (1979) found 2.5% NaOCl to be an excellent solvent of pulp and predentine when specimens were immersed in it. However, when used as an irrigant in conjunction with instrumentation of extracted teeth, 2.5% NaOCl was no more effective in removing pulp than was water.

There is little agreement as to which concentration of NaOCl is the most effective. It is also obvious from the literature that there are other factors influencing its ability to dissolve tissue: such factors may explain some of the conflicting results.

Moorer and Wesselink (1982) carried out an *in vitro* study enabling them to describe the effects of fluid flow, pH and available surface area of the tissue on the dissolving ability of NaOCl. They found that to be effective, the NaOCl solution must be in excess (in terms of weight per volume) of the organic substance to be dissolved. In such a situation, NaOCl lost little of its activity. On the other hand, an excess of organic matter rapidly depleted the activity of NaOCl and lowered the pH drastically during the first moments of the reaction. At a constant surface area, a higher concentration of NaOCl was found to be most effective. Mechanical agitation of NaOCl had a significant effect on tissue-dissolving ability while ultrasonic oscillation had a very strong effect. They concluded that the amount of available chlorine in a hypochlorite system is more important than the initial strength of the solution when considering antimicrobial and solvent ability.

Crabb (1982), in evaluating NaOCl as an irrigant, claimed to have enhanced its cleansing ability by mechanically agitating the irrigant in the canal with a lentulo spiral and by ultrasonic agitation. Unfortunately, no comparison was made between agitated and non-agitated NaOCl.

3.2.3 **Toxicity**

As mentioned above (p.26), an irrigant must have antibacterial properties and tissue solvent ability, and it must be non-toxic to periapical tissues. The toxicity of NaOCl has not been investigated as extensively as the other two properties.

Spangberg et al. (1973) used *He La* cells to study the toxicity of a number of dental materials, and concluded that a 5% solution of NaOCl was "highly toxic and irritating to tissue while 0.5% NaOCl had much reduced toxicity but still retained an antimicrobial effect for all bacteria commonly present in necrotic cases" (p.865). A further advantage, they stated, of 0.5% NaOCl was that it dissolved necrotic but not vital tissue. Thé et al. (1980) implanted polythene tubes containing various concentrations of NaOCl into the backs of guinea pigs in order to study the inflammatory response of connective tissue. They were unable to determine any significant difference in response between NaOCl solutions of 0.9%, 2.1%, 4.1% and 8.4%, concluding that the optimal concentration of NaOCl solution for clinical use is determined mainly by the bactericidal and tissue dissolving requirements. Massilamoni et al. (1981) used human lung fibroblast cells to determine toxicity of various root canal medicaments. NaOCl was diluted 1:5000 before it became non-toxic. The authors questioned the validity of extrapolating from the *in vitro* studies to the clinical situation and suggested the tests serve as initial screening only.

Harrison et al. (1978) carried out a clinical investigation to determine the effect of the use of saline, 5.25% NaOCl and 5.25% NaOCl with 3% H_2O_2. Conclusions were drawn on the basis that toxicity is linked with the incidence of interappointment pain. They found what they termed the "clinical toxicity" of 5.25% NaOCl to be no greater than that of normal saline. Pashley et al. (1985) more recently used three independent biological models to determine the toxicity of NaOCl. They used human red blood cells in an *in vitro* investigation and found that a 1:1000 dilution of Clorox caused 100% haemolysis. In the *in vivo* study, they found that 1 drop of NaOCl, either 5.25% or 0.525%, in the eyes of rabbits caused moderate to severe conjunctival palpebral oedema. Intradermal injections in rats of 5.25% NaOCl produced immediate haemorrhage throughout the entire area of contact of the solution with the tissues. Lower concentrations of NaOCl produced less leakage of plasma proteins. They concluded that NaOCl is a very caustic, non-specific, oxidizing agent. Passed through the apex, this agent had the potential to cause serious side effects ranging from pain and oedema, to sloughing of overlying mucosa. It could cause serious problems if inadvertently dropped in patients' or clinicians' eyes.

There are conflicting reports in the literature on the toxicity of NaOCl. Care must be taken in extrapolating from *in vitro* and animal studies to the clinical situation. As Thé et al. (1980) point out, the irritating effect of an irrigating solution is not only dependent on its concentration but also on the means of its application.

3.2.4 Summary

Review of the literature confirms that the unique set of antibacterial, tissue-dissolving and relatively non-toxic properties of NaOCl are satisfactory and, therefore, that the solution is suitable for endodontic use. Although any concentration of NaOCl between 0.3% and 5.0% may be used successfully in clinical endodontics, it appears that the mechanical aspects of the technique may be as important as the initial hypochlorite concentration. Moorer and Wesselink (1982) concluded that with a better mechanical debridement technique and with more frequent changes of hypochlorite, a lower concentration of irrigant may be used for safe and thorough debridement and disinfection of the root canal system.

3.3 HYDROGEN PEROXIDE

A 3% aqueous hydrogen peroxide (H_2O_2) solution has been used widely as an endodontic irrigant and, in conjunction with 5% NaOCl, is recommended by Grossman (1981, p.241) and Weine (1982, p.319). The effervescence created by the liberation of oxygen helps to carry the debris out of the canal (Grossman, 1943). Weine (1982) suggested that the liberation of oxygen also kills strict anaerobes in the canal.

Contradicting these recommendations are studies, using the SEM, which showed that canals irrigated alternately with 6% NaOCl and 3% H_2O had more debris than those irrigated with NaOCl alone (McComb & Smith, 1975; Blackler, 1983). Thé (1979) found H_2O_2 to be limited in its capacity as an organic solvent and that its use in conjunction with NaOCl inhibited the solvent ability of

NaOCl. When the two solutions were used alternately in the root canal, the release of bubbles of oxygen acted as a barrier to the exchange of fresh solution in the deeper parts of the canal (Abou-Rass & Piccinino, 1982). These findings, along with consideration of the hazards of H_2O_2 as an irrigant, do not support its use as a clinical endodontic irrigant. Complications arising from H_2O_2 injection beyond the apex can be severe: tissue emphysema has been reported by Harris, 1971; Bhat, 1974; and Kaufman, 1981.

3.4 UREA PEROXIDE

Urea peroxide is composed of urea and hydrogen peroxide. Urea is generally non-toxic, well tolerated by vital tissue and, in 30% solution, is a mild, necrotic tissue solvent and antiseptic (Penick & Osetek, 1970). Stewart et al. introduced Gly-Oxide[26] as an endodontic irrigant in 1961. This new product was a 10% solution of urea peroxide in an anhydrous glycerin vehicle. They claimed the solution was more stable and had a greater germicidal activity than aqueous H_2O_2; the glycerin base acting as an excellent lubricant. Its use in conjunction with 5% NaOCl was recommended. Brown and Doran (1975) noted that the above combination produced an effervescence which caused flotation of dentine particles in simulated root canals. Hydrogen peroxide (3%) with NaOCl was less effective in this respect.

3.5 CHLORAMINE T

Chloramine T is composed of chloramine, sodium chloride and water, and is usually used in a 4% aqueous solution. It has little ability to dissolve necrotic tissue (Ingle & Taintor, 1985, p.183).

3.6 CITRIC ACID

Loel (1975) suggested using 50% citric acid alternately with NaOCl when irrigating canals. Wayman et al. (1979) found that when used as an irrigant, citric

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[26] Marion Laboratories, Kansas City, MO, U.S.A.

acid in concentrations of 10%, 25% and 50% cleansed the canal walls and left the dentinal tubules open, whereas 5.25% NaOCl occluded the tubules. Tidmarsh (1978) stated that 50% citric acid cleanser used in conjunction with instrumentation produced a clean wall free of debris, however, copious irrigation was required to avoid residual crystal deposition. Baumgartner et al. (1984) found that irrigation regimens using citric acid, or a combination of citric acid and NaOCl, were more effective than NaOCl alone in removing the smeared layer. Citric acid is well tolerated by periapical tissues (Crigger et al., 1983) and, while it does possess some antimicrobial activity, it is not as effective as NaOCl in this respect (Smith & Wayman, 1986).

3.7 CHELATING AGENTS

The chelating solutions most commonly used for irrigation include ethylene diamine tetra-acetic acid (EDTA) as the chelating ingredient.

Nygaard Ostby (1957) introduced the use of EDTA in endodontics. He recommended a 15% solution buffered to a pH of 7.3. The original formula was modified by the addition of cetrimide, a quaternary ammonium bromide, to enhance bacteriostatic effects and to decrease surface tension (von der Fehr & Nygaard Ostby, 1963). This agent became commercially available under the name EDTAC. Von der Fehr and Nygaard Ostby (1963) tested it on root canal dentine *in vitro* and found it had a rapid but well delimited demineralizing effect which was related to the quantity of reagent present. Because EDTA forms a stable bond with calcium, no further decalcification will take place when all available chelating ions have reacted. Patterson (1963) found that the surface hardness of dentine was greatly reduced by EDTA. He further reported that EDTAC was not injurious to periapical tissue.

During the mid 1970's, reports were made of the ability of EDTA to remove the smear layer from the instrumented surface of the root canal (McComb & Smith, 1975; Baker, 1975; Goldberg, 1977). Since that time, much interest has focused on this property of EDTA and many studies have been carried out using irrigating regimens involving either EDTA alone or EDTA in conjunction with other irrigants (see Section 3.9).

RC prep[27] is a proprietary product developed by Stewart et al. (1969). It is composed of 15% EDTA, 10% urea peroxide and a water-soluble carbowax base. In assessing its effectiveness by use of a culture technique, Stewart et al. concluded that it was an effective aid in cleansing and enlarging root canals. It had good chelating properties and, in conjunction with NaOCl, produced a bubbling action which helped float debris from the root canal. The surface of the canal wall was altered by the agent to permit penetration of a dye substance. These findings were not substantiated by Blackler (1983), who found in a SEM investigation that irrigation with 1% NaOCl combined with the use of RC prep left an extensively smeared canal wall. Zurbriggen (1975) reported that a residue of RC prep is left in the canals in spite of further irrigation and cleansing. According to Cooke et al. (1976), this post-debridement residue significantly increased periapical leakage following canal obturation, but Biesterfield and Taintor (1980) reported no increase in periapical leakage when RC prep was used in preparation. Goldberg et al. (1985) attributed the different findings to varying amounts of carbowax residue. They found no difference in the quality of the apical seal between canals irrigated with saline and those irrigated with 15% EDTAC[28].

Salvizol[29] (aminoquinaldinium diacetate) is another root canal chelating irrigant. It belongs to the surface-acting materials which are similar to the quaternary ammonium group. Kaufman et al. (1978) has suggested that Salvizol, with a neutral pH, has a broad spectrum of bactericidal activity as well as the ability to chelate calcium. This gives the product a cleansing potency while being biologically compatible. Spangberg et al. (1978) compared the toxicity and tissue-irritating qualities of Salvizol against EDTAC and 2% iodine-potassium iodide

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[27] Medical Products Laboratories, Philadelphia, PA, U.S.A.

[28] Edtac Laboratories Farmadental, Buenos Aires, Argentina

[29] Ravensberg, Konstanz, W. Germany

solution. I_2-KI was the most irritating, followed by EDTAC, with Salvizol the least irritating. In an SEM study, Crabb (1982) found that Salvizol was less effective than 5% NaOCl in cleaning the root canal.

3.8 METHOD OF IRRIGATION

Endodontic irrigants are generally deposited within the confines of the root canal by means of a syringe (5 ml or 10 ml) and a fine needle tip. Heuer (1963) and Schilder and Yee (1984) have recommended the use of a 22-gauge needle, Weine (1982, p.319) suggested 25-gauge, Walton (1976) a 27-gauge and Bolanos and Jensen (1980) a 28-gauge needle. Grossman (1981, p.241) recommended that the bevel of the needle should be removed to make it blunt, while Ingle (1985, p.184) stated that a notched tip, which allows for solution to flow back, was more advantageous; the needle should be placed passively in the canal and not engage the walls.

Ram (1977) concluded that removal of debris is a function of canal diameter rather than the solution used and that effective irrigation occurred only in those canals enlarged to at least size 40 apically. He used a 25-gauge needle and stated that small diameter needles seem to be more effective because they pass further into the canal resulting in better exchange. Abou-Rass and Piccinino (1982) compared 4 different irrigating methods and concluded that the proximity of the irrigation needle to the apex plays an important role in removing canal debris. They recommended that, on completion of canal preparation, the canal contents be flushed by means of a 27 or 30 gauge needle placed in the apical third of the canal. Chow (1983), using an artificial system of standardized canals and particles of bead-form gel, concluded that the depth of the needle in irrigation is important as there is little flushing action much beyond the tip of the needle.

Goldman et al. (1976) devised a perforated needle and observed that it delivered irrigating solution very efficiently to all areas of the canal. Drobotij et al. (1980) found this needle to be no more effective than conventional needles.

The literature contains many studies dealing with the effectiveness of various irrigants. There are two schools of thought in comparing these irrigants in terms of their disinfecting and cleaning qualities. In one, a great emphasis is placed on the chemical properties of the irrigant (for example, NaOCl) whereas in the other, the overriding consideration is the mechanical action of the solution as a flushing agent. Some studies concluded that the flushing action is more important than the chemical nature of the irrigant (Baker, 1975; Senia, 1971; Tucker & Mizrahi, 1976; Ram, 1977; Brown & Doran, 1975).

It can be concluded that the method of irrigation may be as important as the irrigant itself. The irrigant must be delivered into the confines of the apical third of the canal where advantage can be taken of its chemical properties as well as the physical properties of flushing and flotation.

3.9 STUDIES COMPARING IRRIGANTS AND METHODS OF IRRIGATION

Numerous *in vitro* studies have been carried out in the past 45 years evaluating the efficacy of various irrigants with reference to their bactericidal and solvent abilities (see pp.27-37). Many of the earlier *in vivo* evaluations of irrigants were made by taking cultures from the root canals before, during and after the instrumentation and the irrigating procedures (Auerbach, 1953; Stewart, 1955; Ingle & Zeldow, 1958; Masterton, 1965; Shih et al., 1970).

In 1973, Morse outlined some of the pitfalls of the culturing techniques in use at the time. Causes of false positive results included: an unsterile operating field, including instruments and absorbent points; penetration of surface microbes; external contamination; and incomplete seal of coronal restoration. Causes of false negatives included: insufficient inoculum; dormant state of the microbes; timing of culture; incubation time; antimicrobial substances in the canal; culture reversals; culture media; and incubation methods (strict anaerobic methods are necessary to give a true picture of the root canal flora). He concluded that the use of a culture as a pre-filling determinant was not warranted because of its many drawbacks. Bystrom and Sundqvist (1981) have since refined the culture technique for experimental purposes where actual bacteria counts are made using a strictly anaerobic method. The possibility of inaccuracies in the earlier studies raises some questions about experiments in which the results of cultures taken were used as a measure of efficacy of the irrigant.

Histological studies using the light microscope did not address this problem (Reig et al. 1952; Senia et al., 1971; Rosenfeld et al., 1978) nor did studies using the electron microscope. Electron microscopy has been used extensively to examine the surfaces of endodontically prepared root canals enabling the evaluation of different instrumentation and irrigating procedures. It has revealed the existence of a smear layer on the instrumented surfaces of root canals. This smear layer has been the topic of much discussion: what it is comprised of; what produces it; what removes it; and whether or not the aims of root canal preparation should include its removal.

3.9.1 SEM Investigations

Baker et al. (1975) confirmed the value of irrigation, regardless of irrigant, in an SEM study where they found canals which were instrumented but not irrigated contained 70% more debris than irrigated canals. They questioned their access design in light of their finding more debris in the coronal third and along one wall of the canal. Pulp dissolution by 5.25% NaOCl was not observed. The chelating agents opened the orifices of tubules but did not remove debris any more effectively. They concluded that the volume was more important than the type of irrigant.

3.9.1.1 Observation of the Smear Layer

The work of McComb and Smith (1975) prompted much of the discussion on smear layer. They noted that, regardless of instrumentation technique, when water was used as the irrigant, the resulting canal surfaces were essentially the same. At low magnification this surface was very smooth, however, at higher magnification, a surface layer was evident. The dentinal tubules were completely obscured by this smeared layer which apparently was not firmly attached to underlying dentine. Irrigating with 6% NaOCl, with 1% NaOCl and with 6% NaOCl in combination with 3% H_2O_2 left this smeared layer intact, whereas REDTA[30] produced a clean canal surface with patent tubules. The use of RC prep and 6% NaOCl produced a smeared surface with much superficial debris; 20% polyacrylic acid removed the smeared layer but left superficial debris.

The presence of a smear layer on the instrumented surfaces of root canals was confirmed by Moodnik et al., 1976; Lester and Boyde, 1977; Rubin et al., 1979; Bolanos and Jensen, 1980. It was noted by both Lester and Boyde (1977) and Rubin et al. (1979) that when specimens were immersed in, either 5% or in 2.5% NaOCl, pulp tissue and predentine were dissolved leaving the calcified calcospherites of dentine exposed. However, in neither study could this be achieved in practice by irrigating canals with NaOCl. Koskinen et al. (1980) examined the effects of 7 different irrigating solutions on the canal wall. The roots of the teeth were split prior to exposure to the test solutions. Demineralizing solutions left smooth dentinal contours but did not remove organic material; while NaOCl removed organic material, including the predentine layer, it had no visible effect on the inorganic portion. Crabb (1982) compared the effectiveness of 15% EDTA, 5% Salvizol and 5% NaOCl as irrigants under conditions of minimal instrumentation. He also found the demineralizing solutions ineffective in removing organic tissue; 5% NaOCl proved to be the most effective cleansing agent under these conditions.

3.9.1.2 Combination Irrigation Regimes

Goldman et al. (1982), in a SEM study, drew attention to the fact that the combination and sequence of irrigants had a bearing on the completeness of canal cleaning. They reamed and filed single rooted extracted teeth and

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[30] REDTA is a commercial preparation of EDTA and cetyl trimethyl ammonium bromide produced by the Roth Drug Co., Chicago, Ill., U.S.A.

compared the effects of the following irrigating regimens: 5.25% NaOCl throughout instrumentation followed by a 20 ml flush of REDTA; REDTA throughout instrumentation followed by 20 ml flush of NaOCl; NaOCl throughout instrumentation followed by 10 ml flush of NaOCl and 10 ml flush of REDTA; and, REDTA throughout instrumentation followed by 10 ml flush of REDTA and a 10 ml flush of NaOCl. The results indicated that NaOCl used during instrumentation was more effective than REDTA. When the two solutions were used as a final flush, the most effective procedure was REDTA followed by NaOCl. From this, the authors speculated that a small component of the smear layer is organic in nature: and that the chelating agent removed the hard tissue leaving some organic tissue behind. The final flush with NaOCl removed the residue of organic tissue producing a clean canal surface with visible, patent tubules.

A later study (Yamada et al., 1983), comparing 8 different irrigating procedures, also found the cleanest canals to be those which were flushed with 10 ml of 17% EDTA followed by 10 ml of 5.25% NaOCl. Flushing with 10 ml of citric acid and then 10 ml of 5.25% NaOCl also removed the smear layer and superficial debris but left bacteria and crystals.

Blackler (1983) also found the combination of a strong organic solvent and a demineralizing agent most effectively cleaned the root canal. NaOCl (5%) removed surface debris and exerted a partial demineralizing effect, and EDTA 15% removed the smear layer and enhanced instrumentation with its lubricant properties.

The combination of NaOCl with citric acid was evaluated by Baumgartner et al. (1984). NaOCl (5.25%) was significantly better than citric acid in removing superficial debris from the apical third of the canal, whereas citric acid used alone, or in combination with NaOCl, was more effective than NaOCl in removing the smear layer. Rome et al. (1985) evaluated the combination of 2.5% NaOCl and gly-oxide as an irrigating regime. There was no difference in the canal surface produced by this regime and that produced by use of 2.5% NaOCl alone.

Baumgartner and Mader (1987) were able to examine the effect of 4 different irrigating regimes on instrumented and uninstrumented canal walls. The test solutions were: saline; 5.25% NaOCl; 15% EDTA; and 5.25% NaOCl used alternately with EDTA. The smear layer was detected on instrumented surfaces only and predominantly in the NaOCl and saline irrigant groups. This, the authors concluded, was consistent with the belief that endodontic instruments translocate and burnish superficial components (organic and inorganic) of the canal wall during instrumentation. The canals irrigated with EDTA had the smear layer removed, but the canal walls were covered by a fibrous textured layer. Those irrigated with a combination of NaOCl and EDTA had surfaces from which the smear layer was completely removed, leaving patent tubular orifices 2.5 - 4.0 μm diameter when NaOCl was the last irrigant. The authors' explanation of these results is that EDTA demineralizes and removes the inorganic component of the smear layer and leaves the organic fibrous content behind. If there is no fibrous layer on the canal wall, EDTA will demineralize the dentine surface to expose the organic matrix; NaOCl then removes this organic matrix of dentine. Saline and EDTA had no effect on the uninstrumented half of the root canal. NaOCl dissolved all pulpal remnants and the predentine, exposing the underlying globular surface of calcospherites. The combination of EDTA and NaOCl completely removed organic pulpal remnants and severely eroded the exposed globular surface of calcospherites. The progressive dissolution of dentine at the expense of peritubular and intratubular dentine resulted in enlarged tubule orifices of 3 - 5 μm diameter.

The studies mentioned so far have used the SEM to look at the surface of the smear layer, which has thus been described as a thin layer occluding the orifices of the dentinal tubules and covering the intertubular dentine of the prepared canal wall. When observed in profile (Mader et al. 1984), it was revealed that the material comprising the smear layer was packed into the dentinal tubules for distances of 4 - 10 μm. No smeared layer was seen on the surface of uninstrumented areas nor was there any tubular packing in these areas.

3.9.1.3 Clinical Implications of the Smear Layer

While the SEM has allowed much to be learnt about the morphology of the smear layer and effects on it of different procedures, it is clear that the clinical implications of this feature need further investigation. Whether the smear layer is beneficial or detrimental to successful root canal therapy is still controversial; it may be beneficial since it reduces the permeability of dentine and prevents or slows the penetration of bacteria into the dentinal tubules (Pashley et al., 1981); or it may be deleterious in protecting underlying microbes or containing microbes itself. The smear layer may also prevent irrigants, medicaments and filling materials from penetrating into the dentine tubules or even contacting the canal wall (McComb & Smith, 1975; Mader et al., 1984; White et al., 1984, 1987).

3.9.2 Summary

Bacteriological evaluation of the root canal as a means of assessing endodontic techniques is only valid if strict anaerobic methods are used. Its value as a pre-filling determinant is questioned in light of the drawbacks inherent in clinically performing this procedure.

Light and electron microscopy have provided a greater insight into the efficiency of irrigation regimes. The SEM has revealed the presence of a smear layer on the instrumented surfaces of canal walls which results from the translocation and burnishing of organic and inorganic components of the surface by endodontic instruments.

The chelating agent, EDTA, used as an irrigant, removes the smear layer due to its demineralizing properties but it is ineffective in the removal of organic pulp debris. NaOCl, on the other hand, is an effective organic tissue solvent but, used as an irrigant, does not remove the smear layer. A combination of the irrigants EDTA and NaOCl, used alternately, was found to produce very clean, smear-free canal walls.

The clinical implications of the smear layer require further investigation.

CHAPTER FOUR

ULTRASOUND IN ENDODONTICS

4.1 ULTRASOUND

Ultrasound is sound energy with a frequency above the limit of human hearing (usually taken as 20 kHz); this is, in fact, a wide spectrum of frequencies ranging from the kHz to the MHz range. The higher MHz frequencies are employed in general medicine while the kHz range (20-50) is used in dentistry (Walmsley, 1987).

The standard sources of ultrasound are magnetostrictive oscillators (electromagnetic energy is converted to mechanical energy) and piezoelectric oscillators (crystal deformation is converted to mechanical energy).

Ultrasonic wave motion requires a supporting medium with qualities of mass and elasticity. Propagation of the wave involves the displacement of successive particles of the medium. Waves are classified as:

a) longitudinal (particle motion is along the axis of propagation);
b) shear or transverse waves (particle motion is perpendicular to the propagation axis); and
c) surface waves (particle movement is restricted to a thin layer at the surface).

The passage of an ultrasonic wave will display different characteristics in different media. For instance, only solids can support shear waves. When fluids are subjected to shear waves, they yield plastically rather than deform elastically.

When ultrasound is passed through a homogeneous medium, energy waves radiate outwards away from the source of energy. At the interface between two homogeneous media, a longitudinal wave incident at an oblique angle to the interface generates two reflected waves - a longitudinal wave and a shear wave. Two refracted waves are generated in the second medium. A reflected wave can either reinforce or reduce the original wave as it travels away from the interface. An increase in pressure is called a standing wave (Wells, 1977, pp.19-20).

In a visco-elastic medium, an ultrasonic wave can lose some of its mechanical energy as heat which is absorbed by the medium. This absorption occurs exponentially along the direction of propagation, resulting in a gradient of energy density which produces a force acting in the direction of decreasing energy density. This force can produce physical streaming of the medium - known as acoustic streaming. The characteristic pattern created by acoustic streaming in fluids consists of inner and outer vortices. The dimensions of the inner vortices in water at an ultrasonic frequency of 20 kHz are very small which means the velocity gradients, and hence the hydrodynamic shear stresses, are large. Any biological material that enters these streaming fields will be subjected to large shear stresses and may possibly be damaged.

If the amplitude of the ultrasonic wave is increased, more heat per unit volume is deposited in the medium. With high intensity signals, the medium becomes stressed to the limit and rupture of the medium begins to occur. The most common version of this phenomenon is cavitation in liquids. The term cavitation actually encompasses all of the linear and non-linear oscillatory motions of gas and/or vapour filled bubbles in an acoustic field. Transient cavitation is the phenomenon in which voids suddenly grow from nuclei in the supporting liquid and then collapse, under the influence of the changing pressure in an ultrasonic field. The whole process occupies an interval of less than the wave period. The collapse of the cavity causes strong pressure pulses, or shock waves, in the supporting liquid which may be of sufficient amplitude to disrupt cells and biological macromolecules. The behaviour of a gas-filled bubble existing in an ultrasonic field of intensity below that necessary to cause transient cavitation is known as stable cavitation (Wells, 1977, pp. 421-443).

4.2 ULTRASOUND IN DENTISTRY

The introduction of ultrasound into dentistry was primarily for cavity preparation and was first evaluated in 1954 by Oman and Applebaum. They used the "Cavitron[31]" ultrasonic industrial machine to prepare cavities *in vitro* (in extracted human teeth), and *in vivo* (in teeth of human and experimental animals). The ultrasonic apparatus consisted of a variable frequency oscillator which fed a high frequency alternating current to the magnetostrictive handpiece through a power amplifier. Inlays of different shapes brazed to the handpiece were used as the cutting tool and rapid vibratory motion transmitted cutting action to an abrasive liquid mixture which washed across the working tip. The authors concluded that this was an efficient and relatively pain free method of cavity preparation. They speculated on the possibility of using the tool without the liquid to generate heat within the root canal in order to dry it prior to filling. Nielsen et al. (1955) described in detail their efforts to make a workable ultrasonic dental unit; rather than attach separate cutting tools, they extended the transducer itself to form a cutting tip and used aluminium oxide and water as the abrasive mix. Despite the initially favourable reports, the concept of ultrasonic cavity preparation did not progress. Cutting rate was slow and visibility was obscured by accumulation of the abrasive slurry.

In 1957, Johnson and Wilson reported on the application of the Cavitron ultrasonic dental unit to scaling procedures. They found it effectively removed calculus if the blunt tip touched the calculus. Only light pressure was necessary and patients found it more comfortable than hand scaling. The effectiveness of the instrument was dependent upon the constant flow of water which cooled the working tip. This application of ultrasonics has been of enormous value in periodontics where it is currently used widely for supragingival calculus and stain removal. The attendant bulk of the apparatus and the necessity of the water irrigant make it less suitable for subgingival debridement (Schluger et al., 1977, p.375).

[31] U.S. Patent No.2,580,716 granted January 1, 1952

In 1957, the application of ultrasound to endodontic procedures was also investigated. Richman (1957) outlined a procedure where forming of the access cavity, the canal opening, the canal widening, drying of the canal, and placement of the sealant were all carried out using the Cavitron ultrasonic dental unit. For the root canal procedure, he attached barbed broaches to remove the pulp. The broaches were then replaced with files of increasing size to complete the preparation. The canal was constantly flooded with NaOCl throughout the procedure and was dried by activating the file in the canal without an irrigant. The author also reported favourably on the use of an ultrasonic bone chisel to perform apicectomies.

Despite the then promising outlook for this concept in ultrasonics in endodontics, nearly 20 years elapsed before it was investigated further.

4.3 ULTRASONICS IN ENDODONTICS

4.3.1 Bactericidal Effects of Ultrasound

In 1976, Martin set out to determine the bactericidal efficiency of ultrasonics in the root canal. The author's interest in ultrasonics was apparently stimulated by the great advances being made in ultrasonic technology with particular reference to sterilization techniques. Ultrasonics alone seldom provided a 100% kill of microorganism (Boucher, 1972). However, adding ultrasonics to a sterilizing agent often accelerated the sterilization process. Boucher (1972) outlined different synergistic systems where this was the case. Sonophotolysis is a combination of ultraviolet and ultrasonics and forms the basis of a compact system developed for bacteriological purification of water. He used the term "sonosynergistic" to describe the bactericidal enhancement of chlorine, formalin, hydrogen peroxide, benzalkonium chloride and alkaline glutaraldehyde by ultrasound.

Martin (1976) investigated the bactericidal effects of ultrasound against four test organisms (*Streptococcus faecalis, Streptococcus mitis, Staphylococcus aureus* and *Esherichia coli*). Instrumented, autoclaved molar teeth were inoculated *in vitro* with the test organism and it was found that ultrasonics alone was insufficient for significant bacterial reduction. However, a synergistic effect of ultrasound with a bactericidal agent (5.5% NaOCl or potentiated acid 1,5 pantanedial) was demonstrated. The output of the laboratory ultrasound generator was 25 watts with a tip displacement of 4 μm at 23 kHz.

Takagi (1977) reported on the irrigating, bactericidal and clinical efficiency of ultrasound (15 W at 28.5 kHz). He was able to demonstrate a synergistic bactericidal effect of ultrasound with NaOCl, trypsin, urea and H_2O_2. Ultrasound was more efficient as an organic tissue solvent than 1% sodium hypochlorite, 5% trypsin, 30% urea or 3% H_2O_2. The SEM study indicated that ultrasound in conjunction with the above cleansing agents produced clean canal walls. Clinically, he found that the use of ultrasound resulted in fewer patient visits.

4.3.2 Cutting Instruments Powered by Ultrasound

Confident of the potential chemical advantages of the use of ultrasound in root canal therapy, Martin and Cunningham turned their interest to the use of ultrasonic energy to power cutting instruments. Ultrasonic and hand-powered K type files were compared for their ability to remove dentine from a standardized canal prepared in a section of root dentine 4 mm thick (Martin et al. 1980a). The energized file was found to remove a significantly greater amount of dentine than hand filing in a fixed time period. Martin et al. (1980b) then tested ultrasonically energized diamond files using the same experimental model and found that these too, were more efficient in removing dentine than hand held K-files.

4.3.3 "Endosonics"

In 1982, Cunningham, Martin and co-workers reported on the effects of what they termed "Endosonics" with respect to:

a) the removal of debris from the root canal (Cunningham et al. 1982a; Cunningham & Martin, 1982);

b) the amount of debris extruded through the apex during instrumentation (Martin & Cunningham, 1982a);

c) the incidence of post-operative pain (Martin & Cunningham, 1982b); and,

d) the reduction of bacterial spores in artificially contaminated teeth (Cunningham et al., 1982b).

Cunningham et al. (1982a) paired recently extracted human teeth according to size and curvature for hand and ultrasonic instrumentation. The irrigant in all cases was 2.5% NaOCl, with 3 mins allowed for the preparation of each canal. Light microscopy was used to evaluate sections at levels 1 mm, 3 mm and 5 mm from the apex. In all eleven pairs of teeth evaluated, the ultrasonic method was found to be superior in canal cleaning ability. Seven pairs of extracted human anterior teeth were used to carry out an SEM study of longitudinal sections of root canals (Cunningham & Martin, 1982) to evaluate the efficiency of the "endosonic" technique with respect to debris removal. An independent observer judged the ultrasonically prepared canals to be the cleanest in all 7 cases. A smear layer was evident in all specimens.

The ultrasonic method and hand instrumentation were both evaluated with reference to the amount of material extruded through the apex during instrumentation (Martin & Cunningham, 1982a). It was concluded that ultrasonic instrumentation produced significantly less extruded material, however, preparation past the apex produced significantly more extruded debris. When evaluating these same techniques clinically, Martin and Cunningham (1982b) were not able to determine any differences in post-operative pain produced by ultrasonic versus hand instrumentation.

Cunningham et al. (1982b) compared the ability of endosonic and hand filing techniques to reduce *Bacillus subtilus* spores in artificially contaminated straight root canals. When sodium chloride was the irrigant, the ultrasonic technique resulted in an 86% reduction in spores compared with a 62% reduction for the hand filed group. However, when NaOCl (concentration not stated) was the irrigant, both the hand and ultrasonic techniques resulted in a 99% reduction in bacterial spores.

In 1985, Martin and Cunningham summarized many of their previous findings and described the "endosonic, ultrasonic, synergistic system of endodontics" which they had thus far developed. Specially made endosonic files and diamond instruments were energized by means of a Cavitron ultrasound generator (≥20 kHz). An endosonic insert was designed to allow 2.5% NaOCl to pass through and along the files. This system, they said, provided a unique coupling of chemical and mechanical debridement. The continuous high volume irrigation interchange increased the ability of the irrigant to dissolve, flush and remove debris. Energizing the irrigant produced physicochemical and physicomechanical effects which enhanced canal debridement: heating and agitation of the irrigant increased its bactericidal and solvent capabilities; cavitation, by producing shock waves, forced the irrigant into otherwise inaccessible areas of the canal and in conjunction with acoustic streaming caused damage and disruption to bacterial cell walls.

Cunningham and Martin found endosonics superior to hand instrumentation in nearly every way; however, Weller et al. (1980) observed differently. In a study using simulated canals and extracted premolar teeth, they found hand instrumentation and ultrasonication (20 secs of ultrasound with a smooth size 15 plugger) equally effective in removing radioisotope-laden gelatin from a root canal. Hand instrumentation followed by ultrasonication was the most efficient method.

4.3.4 Ultrasonic Irrigation

A clinical report on the use of ultrasound in the cleaning of root canals was made by Cameron (1982). After preparation of the canal by hand, the irrigant (3% NaOCl) was activated ultrasonically using a Cavitron dental unit with an endosonic insert number PR30. The amount of debris removed during activation of the irrigant was assessed according to the turbidity of the irrigant. Most of the debris appeared to be removed from the canal during the first minute of ultrasound. Debridement was apparently complete after 3 min. Following this clinical report, Cameron (1983) investigated the effect of the clinical procedure on the smear layer. After preparation, 35 straight canals were subjected to 1, 3 or 5 min of ultrasound. Longitudinal sections were prepared for examination by SEM. He observed that the smear layer seemed to consist of two separate layers: one layer superficial and loosely attached; and the other as dentine or debris plugs in the dentinal tubules. One minute of ultrasound removed the superficial layer only whilst 3 min removed the superficial layer and most of the dentinal tubule plugs. Five minutes of ultrasound removed all debris in instrumented and uninstrumented areas. In a subsequent study (Cameron, 1984), where EDTA-urea peroxide compound was used as an aid in root canal instrumentation, 5 min of ultrasound with 3% NaOCl was not sufficient to remove the smear layer and debris in extracted teeth.

Varying his technique slightly, Cameron (1986) reported clinically on the use of ultrasound in the debridement of infected immature teeth. In these cases, 4% NaOCl was activated in the canal for 5 min in 1 min increments (NaOCl was replenished every min). No conventional instrumentation was carried out. The technique appeared to produce conditions favourable to root end closure using calcium hydroxide paste. In an SEM investigation using 25 extracted single rooted teeth, Cameron (1988) determined that over a 3 min period, 2 min of ultrasonic irrigation with either 4% or 2% NaOCl was an efficient method of removing the smear layer from instrumented areas of the root canal.

4.3.5 Studies Using Straight Root Canals

Further studies using straight canals to evaluate the value of ultrasound in root canal debridement were performed by Cymerman et al., 1983; Tauber et al., 1983; Griffiths and Stock, 1986; Alacam, 1987; Goldman et al., 1988; Baker et al., 1988.

In a SEM investigation, Cymerman et al. (1983) found no difference in the appearance of the canal wall when hand instrumentation was compared with ultrasonic instrumentation. In all teeth, saline was used as the irrigant. A period of 2 min was allowed for instrumentation with the ultrasonic instrument. Both techniques produced a canal surface with irregularities and smeared with tissue debris. A wave pattern was observed on the walls of the ultrasonically instrumented canals.

Tauber et al. (1983), using a magnifying lens (x4) to study the topography of the dentine wall, compared conventional and ultrasonically energized filing. The teeth were irrigated intermittently with 0.5% NaOCl. The period of ultrasonic activity was unspecified. The ultrasonically prepared canals tended to show lower mean values of remaining debris. Both techniques left a considerable amount of debris, although the middle third of the canal was the cleanest.

The value of ultrasound in conjunction with different irrigating regimes was evaluated by Griffiths and Stock (1986) and Alacam (1987). Griffiths and Stock found ultrasonically activated 2.5% NaOCl produced a cleaner canal than either activated Solvidont[32] (a quaternary ammonium compound) or water. Alacam (1987) observed that methods employing ultrasound in conjunction with final irrigation produced clean, smear-free, canal walls.

Using silicon models of instrumented root canals, Goldman et al. (1988) evaluated the apical preparation of hand prepared and ultrasonically prepared root canals where 5.25% NaOCl was used as the irrigant. They found that hand instrumentation produced a superior apical preparation. In the same study, the ability of the techniques to clean the canals was compared using the SEM and no significant differences between the techniques were detected. Baker et al. (1988), in a similar study where 2.62% NaOCl was used as the irrigant, found hand instrumentation superior to ultrasonic instrumentation in the middle third of the canal but no differences between the techniques in the coronal and apical thirds.

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[32] De Trey, Dentsply, Weybridge, Surrey, U.K.

4.3.6 Ultrasound and the Bacteriological Status of the Canal

The bacteriological status of the root canal after ultrasonic preparation has been determined by means of *in vivo* studies involving dogs (Barnett et al., 1985); monkeys (Lindskog et al., 1986) and humans (Sjogren & Sundqvist, 1987).

Barnett et al. (1985) induced root canal infection in single rooted teeth of young dogs. After 7 days, the root canals were instrumented in one of three ways: with conventional hand instruments; with a sonic device (the Endostar 5); or with an ultrasonic device (the Cavi-endo). Sterile saline or 2.5% NaOCl was used as irrigating solution. Seven days later, an anaerobic culturing technique was used to ascertain the bacteriological status of the root canals. Results indicated that sonic and ultrasonic devices were not more effective in the elimination of bacteria from the root canal than hand instrumentation, and that irrigation with NaOCl appeared to be more effective than saline. To achieve bacteria-free root canals in a predictable manner, Barnett et al. concluded it was necessary to use the supporting action of an antibacterial medicament between appointments. Lindskog et al. (1986) induced inflammatory root resorption, itself an indication of the presence of bacteria (Andreasen, 1981), in monkey teeth. The root canals were debrided using a Cavi-endo with endosonic files and continuous irrigation with 0.5% NaOCl. Results were histologically evaluated using a morphometric technique and revealed that ultrasonication eliminated inflammatory resorption. Under similar experimental conditions, hand instrumentation alone did not reduce inflammatory resorption (Hammarström et al. 1986). Lindskog et al. (1986) therefore suggested that this mode of treatment may be of value in the elimination of bacteria inside those dentinal tubules otherwise inaccessible to conventional therapy. Sjogren and Sundqvist (1987) studied single rooted teeth with necrotic pulps and radiographic evidence of periapical bone destruction. The canals were instrumented using a Cavi-endo with endosonic files and continuous irrigation of 0.5% NaOCl. An anaerobic culturing technique was used to ascertain the bacteriological status of the root canals after the first and second appointments. After the first appointment, bacteria persisted in 29% of cases and in 22% of cases after the second appointment. This compared with 55% and 35% respectively for hand instrumentation under similar experimental conditions (Bystrom & Sundqvist, 1983). Sjogren and Sundqvist (1987) concluded that although ultrasonication enhances the procedure of root canal disinfection, the use of an antibacterial dressing between appointments is necessary to achieve as complete a reduction as possible in bacterial levels.

4.3.7 Cutting Efficiency of Ultrasonic Instrument Systems

The cutting efficiency of ultrasonic instrument systems in endodontics has been studied further since the original work of Martin et al. (1980a,b). Miserendino et al. (1988) studied the cutting efficiency of the following instrument systems for their ability to enlarge artificial root canals composed of epoxy resin: the Cavi-endo ultrasonic unit with K-type files and diamond files; the Enac ultrasonic unit[33] with Zipperer U-files[34]; Endostar 5 sonic unit with Endostar K files; and Micro-Mega 3000 sonic unit with rispisonic R files and shaper R-files. The results indicated a greater efficiency of the R-type Micro-Mega and diamond Cavi-endo systems over that of the K-type instruments when used in their respective vibratory systems. The authors attributed this to the combined effects of file design and oscillatory motions created by vibratory systems. The irregular cutting surfaces of the diamond file and the R-type instruments enabled an efficient abrasive cutting action when used in a vibratory system. On the other hand, the helical cutting edge of K-type files and reamers is employed by either rotary or linear motion. Advantages of abrasive cutting are listed by Miserendino et al. (1988) as: a) a uniform reduction of the dentine wall surface; b) the ability to control the smoothness of the dentine surface; c) the removal of dentine by a low level of applied force; and d) the rapidity of the process.

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[33] Osada Electric Co., Tokyo, Japan

[34] Vereinigte Dentalwerke, Munchen, W. Germany

4.3.8 Summary

The application of ultrasound to endodontics was originally documented in 1957 but it was not until 1976 that the concept was pursued. This was at a time when reports were being published on the bactericidal enhancement, with ultrasound, of widely used sterilizing agents. A synergistic bactericidal effect of ultrasound and NaOCl was subsequently found to occur in the root canal and increased cutting efficiency of K-type and diamond files when powered by ultrasound was reported.

The term "endosonics" was introduced to describe a technique by which root canals were prepared using ultrasonically energized files with continuous irrigation of NaOCl. The initial studies found endosonics superior to hand filing in nearly every way but in later reports many authors found little difference between the two. It was generally agreed that the best results were obtained when ultrasound was used in combination with hand filing.

All of the studies reviewed so far have evaluated ultrasonic techniques in straight root canals.

4.4 ULTRASONIC ENDODONTICS IN CURVED ROOT CANALS

By 1985, there were many reports in the literature on the use of ultrasonic systems in the debridement of root canals. These systems were claimed to be superior to hand instrumentation and previously developed mechanical endodontic instruments (Martin & Cunningham, 1985; Giangrego, 1985). However, most of the studies on which these claims were based assessed performance of endosonics in single-rooted teeth with comparatively straight canals. Goodman et al (1985), Chenail and Teplitsky (1985) and Langeland et al. (1985) were among the first to address the problem of the curved canal.

Langeland et al. (1985) performed *in vitro* (using 65 freshly extracted human teeth) and *in vivo* studies (using 106 monkey incisors and canines) to compare hand instrumentation with ultrasonic and sonic instrumentation. They examined horizontal and longitudinal sections and gave a rating for each based on the amount of debris present. Results demonstrated that all 3 techniques fully cleaned straight circular canals, however, none of the techniques totally cleaned curved or irregular canals. It was concluded that the degree to which the canal was debrided depended more on canal anatomy and pathosis than on any particular cleaning device. However, under similar conditions, debridement with sonic and ultrasonic devices proceeded more quickly and with less stress on the operator. They therefore warned that the operator using sonic/ultrasonic techniques should proceed with caution to prevent perforations.

4.4.1 Step-back Hand Instrumentation with Ultrasound

Goodman et al. (1985) evaluated ultrasonics in conjunction with the step-back hand instrumentation technique. They used mesial canals of 60 extracted human mandibular molars which had a degree of curvature ranging from 15-30°. A constant flow of 2.62% NaOCl solution accompanied instrumentation. On completion of hand instrumentation, the irrigant in half of the specimens was ultrasonically activated for a period of 3 min using a size 15 tapered finger plugger placed short of the working length. This was energized by means of a Piezo electric ultrasonic dental unit[35]. All teeth, including uninstrumented control teeth, were decalcified and histologically prepared. A calculation of the total canal and isthmus area was made from horizontal sections 1 mm and 3 mm from the apex. The amount of tissue removed was expressed as a percentage of the total area. At the 1 mm level, the step-back/ultrasonic technique cleaned canals and isthmuses more effectively than the step-back technique. At the 3 mm level, the step-back/ultrasonic technique more effectively cleaned the isthmuses but there was no significant difference in canal cleanliness between the two groups. A difference between operators was observed with the step-back technique but was not obvious with the step-back/ultrasonic technique.

[35] Buffalo Dental Mfg., Brooklyn, NY, U.S.A.

A similar study by some of the same authors (Lev et al. 1987) was carried out to compare the step-back technique with a step-back/ultrasonic technique where the period of ultrasound was varied. The step-back/ultrasonic groups were subjected to either 1 min or 3 min of ultrasound. Statistical analysis indicated no significant differences in canal cleanliness at the 1 and 3 mm levels between any of the techniques. The step-back/3 min ultrasound preparation cleaned isthmuses at the 1 and 3 mm levels more effectively than the step-back or step-back/1-min ultrasound techniques, suggesting that the use of ultrasound for only 1 min did not provide adequate exposure of the activated irrigant to aid in debridement. There were no differences detected between operators for any of the techniques. This finding and those concerning canal cleanliness are in contrast to the previous findings of Goodman et al. (1985). Lev et al. (1987) attributed this difference largely to differences in the debridement techniques used. To standardize the time exposed to the irrigant in the step-back group, Lev et al. (1987) used a size 20 K-file, 1 mm short of working length, in a push-pull motion for 3 min while a constant flow irrigation/aspiration system remained in operation. In the step-back/1-min ultrasound group, a size 20 K-file was used in the same manner for 2 min. Very high levels of canal cleanliness were achieved with all three techniques. The authors speculated that, in a clinical situation, it would not be feasible to utilize such high volumes of irrigant in the step-back preparation and that it would be unlikely to achieve such a high level of cleanliness. For the clinician, therefore, they suggested that an *in vivo* study with intermittent irrigation in the step-back preparation would provide more information.

In 1989, some of the same authors (Haidet et al. 1989) performed an *in vivo* experiment using the mesial canals of lower molars in patients whose teeth were to be extracted for periodontal or other reasons. After extraction, the teeth were histologically prepared and evaluated as in the previous two studies (Goodman et al., 1985; Lev et al., 1987). Step-back instrumentation was carried out with intermittent irrigation of 5.25% NaOCl. On completion of instrumentation, a non-activated endosonic file was used in the canal with the irrigant for 3 min. With the step-back/ultrasound technique, the canals were exposed to 3 min of ultrasound on completion of instrumentation. Both techniques took the same amount of time. At the 1 mm level, the step-back/ultrasonic technique was significantly more effective in cleaning the canals and the isthmus area. At the 3 mm level, there were no significant differences between the two techniques. Haidet et al. (1989) concluded that ultrasonication after instrumentation should be added to the clinical debridement regimen.

4.4.2 **Further Histological Evaluation of Ultrasonic Techniques**

Other authors to carry out histological evaluations of ultrasonic techniques in curved canals were Stamos et al. (1987); Reynolds et al. (1987) and Ciucchi et al. (1989).

Stamos et al. (1987) compared histologically and quantitatively the debridement ability of hand instrumentation with K-flex files and reamers; sonic instrumentation with the Endostar 5; and ultrasonic instrumentation using the Enac and the Cavi-endo. Sterile water was used as the irrigant in all 4 cases. A fifth group using the Cavi-endo with 2.6% NaOCl as the irrigant was included. The teeth were decalcified and prepared for histological sectioning at 1 mm and 3 mm from the apex. For each section, the area of the canals and isthmus was measured and the percentage of tissue removed was calculated. At the 1 mm level, the cleanest canals were produced by the Enac (with sterile water irrigation) and the Cavi-endo with 2.6% NaOCl irrigation. The Cavi-endo with NaOCl irrigation produced the cleanest canals at the 3 mm level and the cleanest isthmus areas at both levels. The Enac and the Endostar techniques were faster than hand instrumentation and the Cavi-endo technique. Use of the sonic and ultrasonic techniques reduced hand and finger fatigue.

To compare the effectiveness of four different methods of root canal instrumentation in small curved canals, Reynolds et al. (1987) carried out a histological examination of 80 canals. The methods compared were: the step-back hand instrumentation technique with 2.6% NaOCl irrigation; sonic instrumentation with the Endostar 5 and water irrigation; ultrasonic instrumentation with the Cavi-endo and 2.6% NaOCl irrigation; and the PZ-KTec ultrasonic unit[36] with tap water irrigation. Following canal preparation and histological processing, coronal, middle and apical cross-sections were examined by light microscopy. Overall, the step-back hand instrumentation technique was more effective than sonic and ultrasonic systems for: a) increasing canal area; b) removing predentine and debris; and c) planing canal walls. The differences were noted primarily in the coronal and middle canal regions; the apical areas showed less contrast between techniques. The authors speculated that the use of the Gates-Glidden burs in the step-back technique was responsible for much of the dentine removed in the coronal two thirds of the canal. They created straight line access to the apical area which enhanced instrument contact resulting in more effective planing of canal walls. From this, they assumed that in conjunction with ultrasonics, step-back hand instrumentation would result in superior root canal debridement. This theory was reinforced by Goodman et al. (1985) and Haidet (1989).

Ciucchi et al. (1989) used the SEM to examine the walls of 40 curved canals to compare the effectiveness of different irrigating procedures on the removal of the smear layer. All the canals were manually instrumented using the step-back technique with intermittent irrigation of 3% NaOCl solution, followed by a final flush of 5 ml NaOCl and then 5 ml of deionized water. Ten canals served as controls, the remaining 30 were equally distributed between three groups and subsequently irrigated with the following: ultrasonic irrigation using the Cavi-endo system with 3% NaOCl for 2 min; continuous flooding of the canal with 15% EDTA for 3 min; and ultrasonic irrigation with 15% EDTA for 2 min. Smear layer was noted over the distribution of dentinal tubule openings for the coronal, middle and apical segments of the canals. Irrigation with NaOCl produced consistently smeared surfaces. Ultrasonic stirring of NaOCl removed the smear layer inefficiently while EDTA produced almost smear-free surfaces. Ultrasound in association with EDTA did not enhance the dissolving capability of this chelating agent. Decreased efficacy of irrigation procedures was observed in the apical region which the authors attributed to the limited size and

[36] Romulus, MI, U.S.A.

pronounced curvature of the canals. These factors, they stated, would limit distribution of the irrigant and prevent the endosonic file reaching the apex. They suggested that, when the endosonic file did reach the apex, it inevitably contacted the dentine wall which induced damping of the files and consequent absorption of most of the transmitted energy.

4.4.3 **Effects of Ultrasonics on Canal Shape**

While histological studies were being made to evaluate the ability of ultrasound to enhance canal debridement in curved canals, other studies were simultaneously investigating the effect on canal shape of ultrasonic debridement techniques (Chenail & Teplitsky, 1985,1988; Pedicord et al., 1986; Kielt & Montgomery, 1987; Calhoun & Montgomery, 1988; Yamaguchi et al., 1988; Tang & Stock, 1989).

Chenail and Teplitsky (1985) carried out an *in vitro* study on extracted human teeth with root curvatures varying from 10^0-110^0 in order to determine whether or not endosonics straightened curved root canals. The root canals were enlarged by hand until a size 15 endosonic file could be placed at working length. A Cavi-endo unit was used with size 15 endosonic files to enlarge the canals until a size 25 K file could be placed at working length. Post-operative and pre-operative radiographs, taken with files in place, were compared using an overlay technique. No measurable alterations occurred in 94% of the canals. The average time required to enlarge the canals from size 15 to 25 was 2.75 min. The authors concluded that endosonics was efficient and could be safely used in curved canals. The same authors (Chenail & Teplitsky, 1988) repeated their study using size 20 and 25 endosonic files in curved canals and found measurable straightening occurred in all canals. The amount of straightening was not proportional either to working length or to the degree of canal curvature.

Pedicord et al. (1986) studied the root canal shape resulting from the use of ultrasonic and step-back hand instrumentation techniques in 63 extracted human teeth (mandibular first and second molars). Instrumentation time was also studied. The mesial canals were instrumented alternating the techniques from one tooth to the next between the buccal and lingual canals. After instrumentation, the roots were sectioned horizontally in the apical middle and coronal thirds and evaluated for shape and location. Hand instrumentation produced significantly better shapes than endosonic instrumentation in the middle and coronal levels of the root, but there was no significant difference in shapes produced by either technique at the apical level. The endosonic technique produced a slot-type cut in the middle and coronal sections which extended to create a stripping perforation in one of the specimens. Pedicord et al. encountered several problems in operating the Cavi-endo unit, including: inability to maintain length; lack of tactile sensation; frequent binding of files in the small curved canals; and fracture of a file in one case.

Kielt and Montgomery (1987) used simulated curved root canals to evaluate the effect on shape of the canal of conventional hand instrumentation, sonic instrumentation (Micro Mega 3000 and Endostar 5), and ultrasonic instrumentation (Cavi-endo and Enac OE-2). All of the techniques, in the middle portion of the canal, removed more canal wall from the inner aspect than from the outer aspect of the curve; whereas in the apical region, the results were the opposite with more of the canal wall being removed from the outer aspect of the curve. The Micro Mega and the Cavi-endo systems transported significantly less at the apex than the Endostar 5 and hand instrumentation techniques. The Micro Mega 3000, Endostar 5 and hand instrumentation transported significantly less in the middle portion of the canal than the two ultrasonic techniques.

Calhoun and Montgomery (1988) used 24 extracted molars to compare the effect of four different preparation techniques on root canal shape. The techniques were compared for: a) their ability to maintain files in the centre of the canals; b) the amount of dentine removed; c) the direction and length of transportation; and d) the final shape of the instrumented canals. The techniques were: i) step-back hand instrumentation; ii) the balanced force hand instrumentation technique using Flex-R files[37]; iii) ultrasonic instrumentation

[37] Union Broach, New York, N.Y., U.S.A.

using the Enac with Flex-R files; and, iv) ultrasonic instrumentation using the Enac with Zipperer files. There were no significant differences between the techniques: all tended to transport the canal in the same direction at the various levels examined. Canals were transported mesially at the apex, while in the middle and coronal thirds, transportation occurred in a distal direction, despite efforts to apply a mesial force. The balanced force technique tended to centre the instrument best and produced round preparations at the apex, while the other groups produced oval preparations. Techniques using the Enac produced the greatest amount of transportation despite the file type. The authors concluded that this was a very aggressive cutting instrument and care must be exercised while instrumenting teeth with narrow curved canals.

Yamaguchi et al. (1988) used simulated canals of varying curvature to determine the effect on shape of 4 min and 5 min preparation with an Enac ultrasonic unit. A contrast medium was put into the canals and radiographed before and after canal preparation. Superimposing the radiographs disclosed changes in canal shape. Deviation of the preparation from the original shape was more pronounced in the 5 min group and increased as canal curvature increased. Ledge formation occurred in all the canals exposed to 5 min of ultrasound and in 60% of those exposed to 4 min.

Tang and Stock (1989a) introduced an *in vitro* model designed to observe instrumentation effects on the shape of curved canals. The model, by use of a contrasting medium and reproducible radiographs, enabled a two-dimensional evaluation of the shape of the root canals before and after preparation. This model was used (Tang & Stock, 1989b) to compare the effects of hand (using K flex files); sonic (Micro Mega 3000 with Helisonic and Rispisonic files), and ultrasonic (Cavi-endo using endosonic files and diamonds) instrumentation on the shape of curved root canals in 60 extracted human lateral incisors and premolars. The results indicated a lower incidence of "apical zip" and "elbow" formation in the ultrasonic preparations when compared with those prepared by hand and the sonic systems, irrespective of canal curvature. A more prominent hourglass shape resulted from the use of hand instruments, particularly in severely curved canals. A distinctive taper was produced by each method. The three techniques showed preferential dentine removal from the convex aspect of the canal in the apical portion and the concave aspect of the canal in the middle portion. A major drawback with this study was failure to precurve any of the instruments - hand, sonic or ultrasonic.

4.4.4 Summary

The apical region of curved canals, and in particular the isthmus areas, were found to be cleaner when prepared by techniques which combined ultrasound with step-back hand instrumentation than by hand instrumentation alone. The difference in canal cleanliness between the two techniques is less noticeable in the coronal region.

Ultrasonic techniques result in a greater deviation from the original canal shape in the coronal region but, in the apical region, differences between hand and ultrasonic techniques with respect to canal shape are minimal.

4.5 MECHANISMS OF ULTRASOUND IN THE ROOT CANAL

In 1987, Walmsley called for a scientific appraisal of endosonics. He claimed that, despite numerous investigations into the clinical efficacy of the endosonic system, there was poor understanding of the possible role of the biophysical aspects of ultrasound. Walmsley (1987) identified certain characteristics of the action of endosonics and outlined areas requiring further investigation. These may be summarized as follows.

a) Production of ultrasound oscillations.

Endosonic instruments oscillate with a maximum displacement amplitude along the longitudinal axis of the instrument. Because the endodontic file is inserted at an angle of 60-90°, it will oscillate in a transverse rather than a longitudinal manner, setting up a characteristic pattern of nodes (minimal displacement) and antinodes (maximal displacement). Investigation is needed into the effects on oscillation of instrument power setting, size and length of the instrument, and width of the canal.

b) Cavitation

Cavitational activity can be demonstrated within the cooling water supply of the ultrasonic scaler. Whether this occurs with the endodontic instrument requires elucidation.

c) Acoustic microstreaming

This is responsible for the continual movement of irrigant around the canal which may potentially disrupt/disaggregate bacteria and debris. To observe acoustic streaming, it is necessary to establish that the file is actually oscillating within the canal.

d) The irrigant

The activity of NaOCl appears to be increased when passed over the oscillating wire. However, the effectiveness of the endosonic system in irrigating the entire length of the canal (especially the apical one third) requires further consideration.

4.5.1 **Investigation of the Biophysics of Ultrasound**

A series of investigations into the biophysical aspects of ultrasound as related to endodontics was carried out by Ahmad et al. (1987a,b,1988) and Ahmad (1989).

4.5.1.1 The Role of Cavitation

Ahmad et al. (1987a) found that the Cavi-endo ultrasonic unit used, as recommended, did not generate transient cavitation. The displacement amplitude of the file was too small to generate a negative acoustic pressure amplitude sufficient to induce cavitation in a solution of NaOCl in a container measuring 100 x 100 x 50 mm. The production of standing waves, and thus cavitation enhancement, would not be possible in a root canal. For this to occur, the boundary must be one half wavelength or 3 cm away. Acoustic streaming was detected within the system but it was postulated that, with the recommended technique of instrumentation, there would be insufficient streaming generated to participate in effective cleaning. The second part of the investigation was a SEM comparison of ultrasonic and hand-instrumented canals in which little difference was detected between the two groups in the amount of remaining debris, although less smear layer was apparent in teeth instrumented ultrasonically. Better debridement was obtained in teeth irrigated with 2.5% NaOCl irrespective of the instrumentation technique used. Damping of the file when in use was postulated as one of the factors responsible for the lack of any discernable difference in the results between the two groups. Damping, or physical restraint of the oscillating file, occurs when the file contacts the canal walls.

Ahmad et al. (1988) investigated the phenomenon of cavitation using the Enac ultrasonic unit. They showed that the inception of cavitation required a threshold amplitude of at least 135 μm generated by a freely vibrating file. To achieve this, a 25 mm size 15 file was used with the power setting of the Enac at 3.5. To allow the file to freely vibrate, the root canals of 20 extracted mandibular canines were enlarged to a size 40. This corresponded to the sum of the diameter of the tip of the cavitating file and twice the displacement amplitude. On completion of instrumentation to size 40, the teeth were divided into 2 groups. All canals were subjected to 5 min of ultrasound with a size 15 file held in the mid-region of the canal accompanied by free flowing 2.5% NaOCl . In Group 1, the power setting was 3.5, a level conducive to cavitation; in Group 2, the power setting was 1.0, at which level cavitation would not occur. No difference was apparent between the two groups in the amount of surface debris present when the specimens were examined by SEM. Both groups exhibited a typical smear layer appearance. Some specimens in the cavitation group exhibited irregularly distributed pits in the canal wall, the bases of which were devoid of smear layer. The authors emphasized the difficulty with which cavitation was reproduced even under ideal conditions. Therefore, it was their opinion that cavitation was unlikely to occur clinically. They pointed out that the results of this study showed that, even when cavitation did occur, it played very little part in debridement of the root canal.

4.5.1.2 The Role of Acoustic Streaming

Ahmad et al. (1987b) studied the effect of file size and power output on acoustic streaming and displacement amplitude using the Cavi-endo as the source of ultrasound. They deduced that, to utilize acoustic streaming for debridement purposes, the optimal situation would be a freely vibrating file of small size subjected to a high power setting. With this information, they modified the recommended technique of Cunningham (1985) to maximise the effectiveness of acoustic streaming. The canals were prepared with the Cavi-endo as recommended, after which a size 15 endosonic file was inserted into the canal to working length and allowed to oscillate freely at a power setting of 2.5 for 5 min with a free flow of 1% NaOCl. An apical seat equivalent to a size 50 was created.

A SEM investigation was carried out in straight root canals to compare this modified technique with that recommended by Cunningham (1985) who used 2.5% NaOCl. Canals subjected to the modified technique were consistently cleaner with a virtual absence of smear layer, particularly in the apical third. Some specimens exhibited undulating wave-patterned surfaces in certain localized areas. More of these wave patterns were present in canals subjected to the modified technique. Ahmad et al. (1987b) stated "The results from this study indicate that the ultrasonic technique can produce very clean canals. An improved understanding of the mechanisms involved is essential to utilize to the maximum the inherent advantages of the instrument". Although the described modified technique of debridement is applicable in straight root canals where there is no impediment to the positioning of the file, it may not prove to be so practical in narrow curved canals which have restricted access to the apical region.

4.5.1.3 The Oscillatory Patterns of Endosonic Files

Walmsley and Williams (1989) studied the effects of constraint (damping) on the oscillatory pattern of endosonic files and showed that the displacement amplitude of the file, when operating in air, was greatest at the tip as it was unconstrained. The design and change in dimensions of each file affected its oscillatory pattern in air. The working tip in a confined space was the most susceptible to constraint which, at an antinode, caused a greater decrease in displacement amplitude than constraint at a node. From their experimental model, the authors extrapolated to a curved root canal and suggested that, when the file was a "tight fit", it would contact dentine at various points along its length (at nodes and antinodes) and thus vibration of the tip could be almost zero. This, they claimed, would explain the variable clinical findings on the efficiency of the system.

An understanding of the oscillatory pattern of endosonic files may give some insight into the nature and likelihood of fracture of these instruments. Generally, Cavi-endo files have exhibited a low incidence of fracture (Scott & Walton, 1987; Ahmad, 1989). This has been attributed to good quality control in manufacture. On the other hand, Zipperer files used with the Enac Ultrasonic Unit have not enjoyed as good a reputation (Ahmad, 1988). In 1989, Ahmad carried out an analysis of breakage of Cavi-endo ultrasonic files during instrumentation. While the overall incidence of instrument fracture was low, those most likely to fracture were the small size 15 files. The fractures observed were of the brittle type and occurred at or near nodes, mostly at the apical ends of the files where displacement amplitudes were at a maximum. No relationship was apparent between the incidence of fracture and either the displacement amplitude or the hardness of the files.