Investigation of selected properties of a resin-based root canal filling material - an in vitro study

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>Area</td>
<td>A</td>
</tr>
<tr>
<td>Amps</td>
<td>Amperes</td>
</tr>
<tr>
<td>BHI</td>
<td>Brain-heart infusion</td>
</tr>
<tr>
<td>BisGMA</td>
<td>Bisphenol-A-glycidyldimethacrylate</td>
</tr>
<tr>
<td>BSD</td>
<td>Backscattered detector</td>
</tr>
<tr>
<td>C</td>
<td>Cold lateral condensation</td>
</tr>
<tr>
<td>CBCT</td>
<td>Cone beam computed tomography</td>
</tr>
<tr>
<td>CEJ</td>
<td>Cement-enamel junction</td>
</tr>
<tr>
<td>C-factor</td>
<td>Configuration factor</td>
</tr>
<tr>
<td>CH</td>
<td>Calcium hydroxide</td>
</tr>
<tr>
<td>CH1</td>
<td>Calcipast1</td>
</tr>
<tr>
<td>CIH</td>
<td>Clinical Impression of Healing</td>
</tr>
<tr>
<td>cm</td>
<td>Centimetre</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td><em>E. faecalis</em></td>
<td>Enterococcus faecalis</td>
</tr>
<tr>
<td>EBDS</td>
<td>Electron backscattered diffraction system</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy dispersive spectroscopy</td>
</tr>
<tr>
<td>EDTA</td>
<td>Ethylenediaminetetraacetic acid</td>
</tr>
<tr>
<td>$E_d$</td>
<td>Elastic modulus of dentine</td>
</tr>
<tr>
<td>$E_f$</td>
<td>Elastic modulus of filling material</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
</tr>
<tr>
<td>FDA</td>
<td>US Food and Drug Administration</td>
</tr>
<tr>
<td>FEGSEM</td>
<td>Field emission gun scanning electron microscope</td>
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<tr>
<td>GP</td>
<td>Gutta percha</td>
</tr>
</tbody>
</table>
\( h \) Thickness of the slice
HEMA Hydroxy-ethyl-methacrylate
IO Iodoform
kg Kilogram
kV Kilo Voltage
MAF Master apical file
Micro-CT Micro-computed tomography
mL Millilitre
mm Millimetre
MMPs Matrix metalloproteinases
MPa Megapascals
MTAD Mixture of a tetracycline isomer, an acid and a detergent
N Newton
NaOCl Sodium hypochlorite
NiTi Nickel-titanium
PAI Periapical Index
PCL Polycaprolactone
PECS Precision etching and coating system
\( r \) Radius of the canal at the apical aspect
\( R \) Radius of the canal at the coronal aspect
R Resilon
rpm Revolution per minute
SD Standard deviation
SEM Scanning electron microscopy
T Thermal compaction
TEM Transmission electron microscope
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>UDMA</td>
<td>Urethane dimethacrylate</td>
</tr>
<tr>
<td>VP</td>
<td>Vitapex</td>
</tr>
<tr>
<td>°C</td>
<td>Centigrade</td>
</tr>
<tr>
<td>µm</td>
<td>Micrometre</td>
</tr>
<tr>
<td>2D</td>
<td>Two dimensions</td>
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<tr>
<td>3D</td>
<td>Three dimensions</td>
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Abstract

Following chemo-mechanical cleaning of the root canal system, the provision of a fluid-tight seal is one of the main requirements for successful endodontic treatment. Gutta percha with a sealer has been considered as the gold standard root canal filling for many years. However, it does not have all the properties of an ideal root canal filling. A resin-based root filling, Resilon, has been introduced which has the advantage of bonding to the root canal dentine forming a “monoblock”. Different properties of Resilon have been investigated, but some properties using different obturation techniques and in retreatment need further investigation.

The aim of this project was to investigate selected properties of Resilon in primary endodontic treatment (quality of obturation using either cold lateral condensation or thermal compaction, and push-out bond strength following the use of different intracanal medicaments) and secondary endodontic treatment (removability using a combination of hand and rotary instrumentation, fracture resistance and leakage resistance following different removal techniques).

Using micro-CT, the volume of voids in root canals obturated with Resilon in comparison with gutta percha using either cold lateral condensation or thermal compaction was investigated. The results showed that there was no significant difference between the two materials regardless of the obturation technique.

The use of Vitapex and iodoform was found to significantly reduce the bond strength of Resilon to dentine in comparison with calcium hydroxide and its aqueous combination with iodoform (Calcipast1).

The effectiveness of the combined use of hand K-files and ProTaper retreatment files in removal of Resilon using either cold lateral condensation or thermal compaction was compared to that of gutta percha. Micro-CT assessment showed that Resilon resulted in significantly more remaining material than gutta percha when thermal compaction was used.

Fracture resistance of retreated roots filled with Resilon was found to be not significantly different from those filled with gutta percha irrespective to the removal technique (either hand K-files or ProTaper retreatment files). Using the same retreatment techniques, dye leakage resistance of root canals re-filled with Resilon was compared with that of primarily treated root canals. The results showed that there was no significant difference in leakage resistance between re-treated and primarily treated root canals.

Obturation with Resilon was shown to have no significant advantage over gutta percha in terms of quality of obturation and fracture resistance in retreated roots. More investigation of the clinical performance of Resilon is required before it can be considered as a replacement for gutta percha.
Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Fatma Asheibi

2014
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The Author

I finished my high school in 1998 with an Excellent grade and achieved second place in the high school unified national exam. I graduated from the School of Dentistry at University of Garyounis in 2004 with a general grade of Excellent. I was given an Outstanding Achievement Award from the School of Dentistry. I then worked at the same school as a teaching assistant in the Conservative Dentistry department till June 2008.

I was awarded a scholarship from the Ministry of Higher Education in Libya to complete my postgraduate study. I joined a one-year full-time MSc programme in Endodontics at the University of Manchester in September 2008. I got my degree with distinction in 2009. I was awarded another scholarship by the Ministry of Higher Education to study PhD. I enrolled in a three-year Non-Clinical PhD programme in Endodontics in April 2010. In June 2012, I won the Friends of the Hebrew University Prize for the best oral presentation for research in the postgraduate presentation day at the School of Dentistry. I volunteered as an Enquiry Based Learning (EBL) tutor at the University of Manchester from September to December 2012.

I have been the lead author of the following papers:

Dedication

In The Name of Allah

And His Blessings

The all knowing, The most wise

I would like to dedicate my work to my beloved parents, the light of my eyes. Whatever I am is due to their hard work, prays and love. Thank you for teaching me to believe in myself, in Allah and in my dreams. There are not enough words to express my appreciation.

This thesis is also dedicated to my loving husband who experienced all the ups and downs of my research. All I have and will accomplish are only possible due to his endless support and encouragement. It is also dedicated to my little angel, the spring of my life, Marya.

I would also like to dedicate this work to my lovely brothers and sisters who were always there for me whenever I need.
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Chapter 1

Review of the Literature
1.1 Introduction

Endodontology is a word derived from Greek language and it means “the knowledge of what is inside the tooth” (1). It is “concerned with the study of the form, function and health of, injuries to and diseases of the dental pulp and periradicular region, their prevention and treatment; the principle disease being apical periodontitis, caused by infection” (2).

Endodontic treatment was first considered in 1728 when Fauchard described a procedure to treat a tooth with an abscess. A cavity was made in the tooth to drain the pus, and then the tooth was left open for two to three months. After that, the pulp chamber was filled with lead foil. Bourdet, in 1757, described what was called “intentional endodontic treatment”, in which the affected tooth was dislocated to cut the nerve and then replaced in its socket. This procedure had also been described hundreds of years earlier by the Arabian physician Avicenna (3).

The first root canal filling was performed by Edward Hudson in 1809 using gold foil. Other filling materials used at that time were paraffin, amalgam and metals. During the 1850s, there was an attempt to fill the root canals with a firm core and cement. The core material consisted of plugs of wood soaked in creosote which was cemented with Hill’s stopping and chloroform or eucalyptus oil. Hill’s stopping contained gutta percha, powdered glass, quick lime, feldspar, and metal fillings. This was the first use of gutta percha in a root canal filling (3). Using a sealer with a gutta percha cone to fill the root canal was proposed by Rickert in 1925. This procedure was then improved by the use of a tool to condense the gutta percha cones laterally and create a space for extra points (4).
In 1931, Rickert and Dixon postulated the “hollow tube theory”. They explained that if a root canal contained gaps, fluids can enter into these spaces and undergo enzymatic degradation. The products of this breakdown then can move into the periapical tissues and may cause inflammation (4). This theory formed the basis for obturating root canals.

1.2 Role of obturation

The role of bacteria in the establishment and progression of endodontic lesions is well documented (5). Thorough chemo-mechanical cleaning of the root canal system results in healing of most periapical lesions (6). The root canal system should then be obturated in three dimensions with an inert material that creates a fluid-tight seal to maintain the achieved level of disinfection and to prevent percolation of bacteria (7).

Total disinfection of the root canal system is not possible because of the inaccessibility of chemo-mechanical cleaning and the complexity of the root canal network (8). Therefore, some micro-organisms may remain in the root canal or be trapped in dentinal tubules. The obturation material hinders the release of these residual micro-organisms and prevents the in-flow of nutrients. In most cases, the presence of the micro-organisms appears not to influence the outcome of the root canal treatment (9). Although obturation may not be the most critical step in endodontic treatment, it should be performed to the highest standards.

Leakage of bacteria and fluids from the oral environment into the root canal can occur not only before or during endodontic treatment, but also after the treatment is finished. This leakage may lead to failure of the endodontic treatment (10). Leakage can occur by: dissolution of the sealer by saliva, percolation of saliva in the gap
between either the sealer and the root canal walls, the sealer and the core material, or through voids in the obturating materials (11).

Voids within the filling materials, which are not linked to gaps at the periphery of the filling, could be considered less clinically significant because micro-organisms, if present, are restrained in an unfavourable environment and do not have access to a nutritional supply, unless connected with peripheral gaps. Peripheral gaps along the dentine-sealer or core material-sealer interfaces may jeopardize the outcome of root canal treatment. This is because they may act as a pathway that permits sealer dissolution and passage of micro-organisms through the filled root canal to the periradicular tissues. Furthermore, if residual micro-organisms remain trapped in the dentinal tubules after treatment is finished, the peripheral gaps may form channels through which the micro-organisms can get access to nutrients and initiate or continue the inflammatory process (12).

1.3 Obturation materials

Many of the materials that are currently used in root canal therapy have been thoroughly investigated. Knowing the properties of the materials used can help practitioners in selecting the appropriate one for each case. Introducing new materials and improving the existing ones can be aided by studying their clinical performance (13). There are several types of root canal filling materials, such as gutta percha, resin-based fillings (e.g. RealSeal, EndoRez), silicone-based fillings (e.g. GuttaFlow) and glass ionomer-based fillings (e.g. ActiV GP). In the following section selected properties of gutta percha and RealSeal system are reviewed.
1.3.1 Gutta percha

Gutta percha has long been the obturation material of choice of many dentists. The first use of gutta percha in dentistry is credited to Dr. Asa Hill (3). Numerous materials have been introduced with claims that they are better than gutta percha. However, to date no material has been as widely acknowledged as a root filling like gutta percha, since it has many of the properties of an ideal root canal filling which are (14):

1. Easy to manipulate with sufficient working time.
2. Dimensionally stable.
3. Provides a three-dimensional seal with an ability to conform to root canal irregularities.
5. Not affected by tissue fluids.
6. Radiopaque.
7. Does not cause tooth discolouration.
8. Can be easily removed from the canal if retreatment is required.
9. Have antimicrobial properties.
10. Sterile.

Gutta percha is extracted from the mazer wood tree. The two main components of gutta percha are zinc oxide and gutta percha (Table 1.1). It is the trans-isomer of polyisoprene and has two crystalline phases: alpha and beta. The form that exists naturally is the alpha form, which if heated above 65°C, changes to an amorphous form. When the amorphous form is cooled, the resulting phase depends on the rate of cooling. Very slow cooling (0.5°C per hour) results in the reformation of the alpha
phase, whereas fast cooling results in recrystallization in the beta form. The gutta percha which is used in endodontic treatment is in the beta phase (15). However, for thermoplastic obturation techniques, the alpha phase gutta percha is preferred because it undergoes less shrinkage on cooling (16).

**Table 1.1** Composition of gutta percha (17)

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc oxide</td>
<td>65%</td>
</tr>
<tr>
<td>Gutta percha</td>
<td>20%</td>
</tr>
<tr>
<td>Radiopacifiers</td>
<td>10%</td>
</tr>
<tr>
<td>Plasticisers</td>
<td>5%</td>
</tr>
</tbody>
</table>

1.3.2 **Resin-based root canal filling materials**

The lack of adhesion of gutta percha to root canal dentine or conventional sealers has led to the introduction of resin-based root canal filling materials. These materials are capable of bonding to methacrylate-based sealers which in turn bond to the root canal wall forming a “monoblock” which may enhance the seal and strengthen the root canal treated tooth (18).

Resilon was introduced in 2004 under the name RealSeal® (Pentron Corp., Wallingford, CT, USA) (19). A Resilon cone is comprised of a matrix which is composed of co-polymer of polycaprolactone (PCL) and urethane dimethacrylate (UDMA), bioactive glass and radiopaque fillers (bismuth oxychloride and barium
The dimethacrylate component enables Resilon to be bonded to various
dual-cure methacrylate-based resin sealers e.g. Epiphany and RealSeal (20).

The form and handling properties of Resilon are similar to gutta percha. It is
available in ISO standardised cones in 0.04 and 0.06 tapers. It is also available in
pellets which can be used for backfilling using warm thermoplastic injection
techniques. It can be removed for retreatment by softening with heat or dissolving
with solvents (21, 22). The melting point of Resilon is the same as that of gutta
percha (60°C) (23). It has a two-step, self-etching adhesive system.

PCL, which is the main component of Resilon, is a biocompatible biodegradable
polymer that has previously been used as a biomedical material in drug delivery (24).
It has strong mechanical properties, low viscosity and a low melting point. It has a
good resistance to water, solvents, oil and chlorine. Total degradation of this
polymer may take up to two years. Its chemical structure enables compatible
blending with a wide range of polymers while maintaining many of its own
properties (24). The thermoplasticity of Resilon is derived from PCL, whereas its
ability to bond to methacrylate-based sealers is because of the dimethacrylate
monomers which are blended into the polymer (25). Tay et al. (26, 27) reported that
PCL was susceptible to alkaline and enzymatic degradation via ester bond-cleaving
enzymes which might be present in saliva or in the extracellular fluid of endodontic
micro-organisms.

PCL has a low glass transition temperature (-60°C). Glass transition is a unique
property of polymers. A polymer is hard and brittle as glass at a temperature below
its glass transition temperature. This is called the “glassy state”. When the
temperature is elevated above the glass transition temperature, the polymer becomes soft and pliable. This is called the “rubbery state” (25).

The resin-based sealer which is used in conjunction with Resilon is a lightly filled, dual-cure, methacrylate-based material. The matrix is a mixture of bisphenol-A-glycidyldimethacrylate (BisGMA), urethane dimethacrylate (UDMA), ethoxylated BisGMA and hydrophilic difunctional methacrylates. The fillers in the sealer are calcium hydroxide, barium glass, barium sulphate and silica (70% by weight) (28). Table 1.2 summarises the composition of Resilon core material and its sealer.

**Table 1.2** Composition of Resilon cone and sealer

<table>
<thead>
<tr>
<th></th>
<th>Organic component</th>
<th>Inorganic component</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resilon cone</strong></td>
<td>Polycaprolactone and UDMA</td>
<td>Bioactive glass, bismuth oxychloride and barium sulphate</td>
</tr>
<tr>
<td><strong>Resilon sealer</strong></td>
<td>BisGMA, UDMA, ethoxylated BisGMA and hydrophilic difunctional methacrylates</td>
<td>Calcium hydroxide, barium glass, barium sulphate, and silica</td>
</tr>
</tbody>
</table>
The acid and primer are combined in one bottle, eliminating one step in the adhesion process (self-etch primer). The primer, which is an aqueous solution of an acidic monomer, penetrates the smear layer and demineralises the dentine. The primer is composed of a sulphonic acid terminated monomer, hydroxyethyl methacrylate (HEMA), and a polymerisation initiator (29). Paper points are used to remove the volatile carrier part in the primer. The sealer is then applied and polymerised after completion of root canal filling. There is no washing step in this system. Therefore, the smear layer is incorporated into the hybrid layer (30).

1.4 Comparison between gutta percha and Resilon

The literature contains many studies which compare Resilon with gutta percha. These studies have been reviewed and categorized according to the property under investigation: biocompatibility, quality of obturation, leakage resistance, root fracture resistance, bond strength and treatment outcome.

1.4.1 Biocompatibility of Resilon in comparison with gutta percha

As filling materials may come into direct contact with the periapical tissues, their biocompatibility should be carefully assessed. Resilon has been found to be non-toxic and has been approved by the US Food and Drug Administration (FDA). Skin sensitisation to Epiphany sealer was also tested and was found to be insignificant (28).

Bodrumlu et al. (31) compared the biocompatibility of Resilon to that of gutta percha. Both materials were directly implanted into the subcutaneous tissue of rats. Severe inflammation was caused by both materials by the seventh day, but this then
subsided by the 60th day and the materials were well tolerated by the surrounding tissues. When testing for biocompatibility, the long term harmful reaction of tissues to a material is more important than the short term reaction. The results revealed that the inflammatory responses to Resilon were comparable to gutta percha and therefore it has an acceptable level of biocompatibility. This is in agreement with studies by Gracia et al. (32), Key et al. (33), Scotti et al. (34) and Onay et al. (35) who showed that a Resilon/Epiphany root canal filling had a satisfactory tissue response.

In a study by Donadio et al. (36) using an in-vitro cell culture, Resilon showed significantly more viable cells than both gutta percha and Activ GP at any test time. In contrast, Economides et al. (37) reported that the cytotoxicity of Resilon significantly increased with time and it was more than that of gutta percha.

Brasil et al. (38) evaluated periapical repair following chemo-mechanical preparation and root filling with Resilon in comparison with gutta-percha in dog’s teeth (38). Radiographic and histological examination showed regenerative changes in both groups. The biocompatibility of Resilon was considered equivalent to gutta percha.
1.4.2 Quality of obturation with Resilon in comparison with gutta percha

James et al. (39) compared the contents of canals filled with gutta percha/AH-26 sealer to canals filled with Resilon/Epiphany using a continuous wave compaction technique by assessing the percentage of core material, sealer, voids and debris. The roots were cross-sectioned (2, 4 and 6 mm from the apex) and examined using scanning electron microscopy. The results showed no significant difference between the two groups. This is in agreement with a study by Gulsahi et al. (40) in which the roots were also sectioned, but were examined using a stereomicroscope. On the other hand, a study by Hammad et al. (41) reported that gutta percha/Tubliseal sealer (zinc oxide eugenol-based) group showed the lowest percentage of voids compared with Resilon, GuttaFlow and EndoRez. In this study, a more accurate method of assessment, micro-computed tomography (micro-CT), was used.

Epley et al. (42) investigated the completeness of root canal obturation with gutta percha in comparison with Resilon using either cold lateral condensation or continuous wave of compaction. The filled roots were cross-sectioned and examined using a stereomicroscope. They found that a gutta percha/cold lateral condensation group showed significantly more voids than a gutta percha/thermal condensation group, Resilon/cold lateral condensation and Resilon/thermal condensation.

The surface area of voids and gaps in root canals filled with Resilon was compared with gutta percha/AH Plus and gutta percha/MetaSEAL (a resin-based sealer) (43). The obturated roots were cross-sectioned and the slices were digitally photographed using a stereomicroscope. Analysis of the images revealed no significant difference in the area of voids and gaps between the tested materials. A sample from each group
was then examined by SEM. Small voids could be seen within the AH Plus and MetaSEAL sealers in the coronal sections, whereas in the apical sections, no voids were detected. The opposite was observed in the Resilon-filled sections; no gaps were seen in the coronal sections, whereas the apical sections contained gaps. This was explained by the restricted accessibility of the self-etch primer of Resilon to the apical area.

Alicia Karr et al. (44) compared the flow of Resilon into lateral canals and root canal depressions by continuous wave condensation with that of gutta percha. A split-tooth model was used in which lateral grooves and depressions were prepared at 1, 3, 5, and 7 mm from the working length. There were six groups in the study. Three groups were filled with gutta percha using System B at three levels (3, 4 and 5 mm from the working length). The other three groups were filled with Resilon at the same levels in the gutta percha groups. The results showed that Resilon and gutta percha flowed similarly into lateral canals and depressions. However, when the System B plugger was inserted into the canal to 3 or 4 mm, gutta percha filled the lateral grooves 1 mm from the apex significantly better than Resilon. It was observed that no extrusion beyond the working length occurred in either groups. Also, there was no space between the filling using System B and backfill using Obtura II.

The effectiveness of filling lateral canals with Resilon was compared with two brands of gutta percha: Obtura gutta percha (Obtura Spartan, Fenton, USA) and EndoFlow gutta percha (Endopoints Indústria e Comércio Ltda. Paraíba do Sul, Brazil) (45). Artificial root canals were used in which lateral canals were made at three levels (4, 8 and 12 mm from the apex). The roots were filled with the materials using Obtura II. The filled roots were examined using digital radiographs which
were analysed using software. Resilon and EndoFlow gutta percha filled the lateral canals more effectively than Obtura gutta percha at the three examined levels. Karabucak et al. (46) also found that Resilon showed a significantly deeper penetration into lateral canals than standard gutta percha. Different brands of gutta percha may contain different percentages of gutta percha polymer which may influence plasticity and flow (47).

1.4.3 Leakage resistance of Resilon in comparison with gutta percha

The provision of a fluid-tight seal after completion of root canal cleaning and shaping is crucial for the success of the treatment (7). Failure can occur due to leakage of fluids and micro-organisms through poorly obturated root canals (10).

Microbial leakage by Streptococcus mutans and Enterococcus faecalis in gutta percha-filled root canals was compared with that of Resilon-filled root canals using cold lateral condensation and thermal obturation techniques (48). A split-chamber model was used which consisted of upper and lower chambers. Bacteria were placed in the upper chamber in which the coronal part of the root projected through an opening at the lower end. The apical part of the root was immersed in a broth in the lower chamber which contained a pH indicator. Bacteria could only reach the lower chamber through the filled root canal. After completion of the leakage test, which was performed over a period of 30 days, one sample from the Resilon group and another from the gutta percha group were selected. They were sectioned vertically and the dentine-filling interface was examined by scanning electron microscopy (SEM). The results of the microbial test showed that Resilon had significantly better leakage resistance than gutta percha regardless of the technique of obturation. The
findings from the SEM examination showed a gap between the gutta percha and the resin sealer (AH-26) which formed resin tags into the dentinal tubules. No gap could be seen in the Resilon sample. This finding was also observed by Nawal et al. (49), but was contradicted by De-Deus et al. (50) who found that significantly more gaps between the sealer and dentine were seen in Resilon than in gutta percha/AH Plus. Perdigão et al. (51) also reported the presence of wide interfacial gaps in gutta percha/AH-26 filled root canals, but no resin tags could be seen. They also found areas of cohesive separation in the RealSeal sealer. Resin tags were rarely seen in the apical area of Resilon-filled root canals.

Another study by Shipper et al. (52) used a dog model to compare the ability of gutta percha/AH-26 in preventing apical periodontitis with that of Resilon. Cold lateral condensation and continuous wave of compaction techniques were used in this experiment. The obturated teeth were inoculated coronally with micro-organisms from the dog’s teeth before sealing the access cavity. After 14 weeks, histological examination was performed. 82% of the gutta percha-filled roots showed mild inflammation compared to only 19% of the Resilon-filled roots, which was a statistically significant difference. This is in agreement with a study by Leonardo et al. (53) in which histological examination of dog’s teeth was also used. No significant difference was found between the two techniques of obturation with both filling materials. This finding was also reported by Verissimo et al. (54), but was contradicted by Silveira et al. (55) who found that gutta percha used with cold lateral condensation leaked significantly more than with continuous wave of compaction technique.
The results from the studies by Shipper et al. (48, 52) were confirmed by subsequent studies which showed the superior sealing ability of Resilon, despite different methods of assessment (49, 54-63). The superiority of Resilon may be attributed to the formation of a monoblock, in which the core material, sealer, and dentine are closely adhered in the form of a single unit. In contrast, gutta percha has no adhesion to the sealer which may lead to leakage through the gap between gutta percha and the sealer (48).

In contrast to the aforementioned studies, studies by Santos et al. (64), Hirai et al. (65), Onay et al. (66), Pasqualini et al. (67), Paque and Sirtes (68) and Saleh et al. (69), reported that Resilon permitted significantly more leakage than gutta percha. In the studies by Hirai et al. (65) and Paque and Sirtes (68), only the apical 5 mm and 4 mm respectively, was assessed by fluid filtration. Santos et al. (64), who also used the fluid filtration method, found that the sealing ability of both materials significantly improved after storage in 100% humidity at 37°C for 180 days. This finding was unexpected as it was shown that the sealing ability of the filling materials decreased after long-term storage (68, 70). Resilon leaked significantly more than gutta percha/AH Plus at both periods of observation (immediate and 180-day intervals). It was also found that a sound coronal restoration significantly reduced leakage.

Paque and Sirtes (68) found that the apical sealing ability of Resilon and gutta percha/AH Plus showed no significant difference when assessed immediately, whereas after 16 months, the sealing ability of Resilon was significantly lower than that of gutta percha/AH Plus. The deterioration of the seal of Resilon over time was also reported by Kokorikos et al. (71).
Using bacterial leakage tests, Saleh et al. (69) found that in the absence of the smear layer, Resilon leaked significantly more than gutta percha/AH Plus. SEM examination revealed that bacteria colonised the sealer-dentine and gutta percha-sealer interfaces in the gutta percha group, whereas they colonised the sealer-dentine interface and within the sealer in the Resilon group.

In the study by Pasqualini et al. (67), a new homogenous method for sequence detection was used to assess the existence of *E. faecalis* microleakage through root canals filled with gutta percha or Resilon. This method is known as “One Cut Event AmplificantioN (OCEAN)”. In this method, an anchor bonds to the DNA of *E. faecalis* and then a fluorescent labelled amplifier is attached to them. An enzyme, endonuclease, causes fragmentation of the ternary structure. The amplifier is broken into two segments releasing the fluorescent label which is used as an indicator for the presence of *E. faecalis*.

Jack and Goodell (72) compared leakage through root canals filled with Resilon with those filled with gutta percha/Roth sealer (a zinc oxide eugenol-based sealer) using a fluid filtration model. The results showed that gutta percha had significantly better leakage resistance than Resilon. However, in the gutta percha group, a 4 mm intra-orifice barrier was placed which was not placed in the Resilon group.

The suboptimal performance of Resilon in comparison with gutta percha reported in these studies may be explained by several factors that make the adhesion to root canal dentine challenging. These problems are discussed later in this review.

On the other hand, other studies have shown that Resilon and gutta percha/AH Plus or AH-26 have equivalent ability to prevent leakage (71, 73-84). Tay et al. (85) used
SEM to detect gaps at the interfaces between dentine, sealer and filling materials. This revealed gaps in canals filled with Resilon and gutta percha. A similar finding was reported by Pawińska et al. (20). Tay et al. (85) also used the silver tracer penetration technique which revealed silver traces along the sealer-gutta percha interface and the sealer-hybrid layer interface in Resilon when examined by a transmission electron microscope (TEM).

Shokouhinejad et al. (79) reported that there was no significant difference in the sealing ability of Resilon in comparison with gutta percha when the smear layer was removed using ethylenediaminetetraacetic acid (EDTA) or a mixture of a tetracycline isomer, an acid and a detergent (MTAD). The smear layer removal was found to have no significant effect on the sealing ability of the filling materials (86).

The coronal and apical sealing ability of Resilon was compared with that of gutta percha/AH Plus using a dye leakage test (87). The external surface of the filled root was coated with two layers of ethyl cyanoacrylate leaving the access cavity and apical foramen uncovered. The teeth then were immersed in methylene blue dye for two days. Afterwards, the roots were sectioned vertically and they were scanned for dye penetration. The results showed that both groups had equivalent coronal sealing ability. The apical leakage resistance of Resilon was significantly better than gutta percha.

Keçeci et al. (88) evaluated the leakage resistance of various combinations of Resilon and gutta percha with AH Plus and Epiphany sealers using cold lateral condensation or thermal obturation techniques using a glucose penetration test for 90 days and then a fluid filtration test. Results from the glucose penetration showed that the combination of Resilon/AH Plus/cold lateral had significantly better sealing
ability than all of the other combinations. However, the fluid filtration model did not detect any significant difference between the tested groups.

Shemesh et al. (89) reported that a glucose penetration test revealed that Resilon had significantly more apical leakage than gutta percha/AH-26, whereas the fluid filtration method did not show any significant difference. Another study by Shemesh et al. (83) also used glucose penetration and fluid filtration to compare the coronal leakage resistance of Resilon with that of gutta percha/AH-26, but both methods showed no significant difference between the two materials.

The ability of Resilon and gutta percha to entomb *E. faecalis* in the dentinal tubules in bovine root dentine was investigated (90). Blocks of bovine root dentine were inoculated with *E. faecalis* and then filled with Resilon, gutta percha/zinc oxide eugenol-based sealer or gutta percha/resin-based sealer. The filled blocks were incubated for four weeks in brain-heart infusion (BHI) agar. At one, two, three and four weeks, some dentine blocks were taken for analysis. Filling materials were removed and dentine chips from the canal walls were examined. Results showed that all groups had regrowth of the bacteria with no significant difference between them. However, Resilon showed a significant reduction in bacterial regrowth over time.

Tables 1.3, 1.4 and 1.5 provide a summary of the studies that compared leakage resistance of root canals filled with Resilon to those filled with gutta percha.
Table 1.3 Studies which found that Resilon had a significantly better leakage resistance than gutta percha

<table>
<thead>
<tr>
<th>Study</th>
<th>Method of assessment</th>
<th>Sample size</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipper <em>et al.</em> 2004 (48)</td>
<td>Bacterial leakage</td>
<td>156</td>
<td>30 days</td>
</tr>
<tr>
<td>Shipper <em>et al.</em> 2005 (52)</td>
<td>Bacterial leakage (animal study)</td>
<td>56</td>
<td>14 weeks</td>
</tr>
<tr>
<td>Silveira <em>et al.</em> 2007 (91)</td>
<td>Dye penetration</td>
<td>54</td>
<td>5 days</td>
</tr>
<tr>
<td>Leonardo <em>et al.</em> 2007 (53)</td>
<td>Bacterial leakage (animal study)</td>
<td>60</td>
<td>90 days</td>
</tr>
<tr>
<td>Sagsen <em>et al.</em> 2006 (61)</td>
<td>Fluid filtration</td>
<td>36</td>
<td>7 days</td>
</tr>
<tr>
<td>Stratton <em>et al.</em> 2006 (59)</td>
<td>Fluid filtration</td>
<td>140</td>
<td>Immediate</td>
</tr>
<tr>
<td>Nawal <em>et al.</em> 2011 (49)</td>
<td>Bacterial leakage</td>
<td>40</td>
<td>30 days</td>
</tr>
<tr>
<td>Bodrumlo and Tunga 2006 (63)</td>
<td>Dye penetration</td>
<td>42</td>
<td>3 days</td>
</tr>
<tr>
<td>Bodrumlo and Tunga 2007 (57)</td>
<td>Dye penetration</td>
<td>72</td>
<td>Centrifuge for 5 minutes</td>
</tr>
<tr>
<td>Tunga and Bodrumlu 2006 (62)</td>
<td>Fluid filtration</td>
<td>66</td>
<td>3 hours</td>
</tr>
<tr>
<td>Verissimo <em>et al.</em> 2007 (92)</td>
<td>Dye penetration</td>
<td>70</td>
<td>7 days</td>
</tr>
<tr>
<td>Shashidhar <em>et al.</em> 2011 (60)</td>
<td>Bacterial leakage</td>
<td>90</td>
<td>30 days</td>
</tr>
<tr>
<td>Ishimura <em>et al.</em> 2007 (93)</td>
<td>Dye penetration</td>
<td>28</td>
<td>30 days</td>
</tr>
<tr>
<td>Wedding <em>et al.</em> 2007 (56)</td>
<td>Fluid filtration</td>
<td>46</td>
<td>90 days</td>
</tr>
<tr>
<td>Aptekar and Ginnan 2006 (58)</td>
<td>Dye penetration</td>
<td>105</td>
<td>3 months</td>
</tr>
</tbody>
</table>
Table 1.4 Studies which found that Resilon had a significantly lower leakage resistance than gutta percha

<table>
<thead>
<tr>
<th>Study</th>
<th>Method of assessment</th>
<th>Sample size</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santos et al. 2010 (64)</td>
<td>Fluid filtration</td>
<td>82</td>
<td>180</td>
</tr>
<tr>
<td>Hirai et al. 2010 (65)</td>
<td>Fluid filtration</td>
<td>64</td>
<td>8 minutes</td>
</tr>
<tr>
<td>Onay et al. 2009 (66)</td>
<td>Fluid filtration</td>
<td>120</td>
<td>8 minutes</td>
</tr>
<tr>
<td>Pasqualini et al. 2008 (67)</td>
<td>Bacterial leakage</td>
<td>88</td>
<td>47 days</td>
</tr>
<tr>
<td>Paque and Sirtes 2007 (68)</td>
<td>Fluid filtration</td>
<td>90</td>
<td>Immediate/1 6 months</td>
</tr>
<tr>
<td>Shemesh et al. 2006 (89)*</td>
<td>Glucose leakage/Fluid filtration</td>
<td>120</td>
<td>56 days/8 weeks</td>
</tr>
<tr>
<td>Saleh et al. 2008 (69)</td>
<td>Bacterial leakage</td>
<td>110</td>
<td>135 days</td>
</tr>
<tr>
<td>Jack and Goodell 2008 (72)</td>
<td>Fluid filtration</td>
<td>34</td>
<td>Immediate</td>
</tr>
</tbody>
</table>

*In this study, the fluid filtration method revealed no significant difference between the two filling materials
Table 1.5 Studies which found that Resilon and gutta percha had an equivalent leakage resistance

<table>
<thead>
<tr>
<th>Study</th>
<th>Method of assessment</th>
<th>Sample size</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>de Almeida-Gomes et al. 2010</td>
<td>Bacterial leakage</td>
<td>140</td>
<td>Coronal: 15 weeks, apical: 30 days</td>
</tr>
<tr>
<td>Fransen et al. 2008 (74)</td>
<td>Bacterial leakage</td>
<td>73</td>
<td>65 days</td>
</tr>
<tr>
<td>Karapinar-Kazandag et al. 2010</td>
<td>Glucose leakage</td>
<td>120</td>
<td>3 weeks</td>
</tr>
<tr>
<td>Williamson et al. 2009 (75)</td>
<td>Bacterial leakage</td>
<td>70</td>
<td>40 days</td>
</tr>
<tr>
<td>Biggs et al. 2006 (80)</td>
<td>Fluid filtration</td>
<td>96</td>
<td>Immediate</td>
</tr>
<tr>
<td>Raina et al. 2007 (84)</td>
<td>Fluid filtration</td>
<td>22</td>
<td>7 days</td>
</tr>
<tr>
<td>Oddoni et al. 2008 (87)*</td>
<td>Dye leakage</td>
<td>24</td>
<td>48 hours</td>
</tr>
<tr>
<td>Shokouhinejad et al. 2010 (79)</td>
<td>Bacterial leakage</td>
<td>100</td>
<td>60 days</td>
</tr>
<tr>
<td>Baumgartner et al. 2007 (95)</td>
<td>Bacterial leakage</td>
<td>36</td>
<td>50 days</td>
</tr>
<tr>
<td>Kaya et al. 2007 (78)</td>
<td>Glucose leakage</td>
<td>156</td>
<td>30 days</td>
</tr>
<tr>
<td>Shemesh et al. 2007 (88)</td>
<td>Glucose leakage and fluid penetration</td>
<td>50</td>
<td>Glucose test: 4 weeks followed by fluid filtration</td>
</tr>
<tr>
<td>Shin et al. 2008 (90)</td>
<td>Bacterial leakage</td>
<td>160</td>
<td>4 weeks</td>
</tr>
<tr>
<td>De-Deus et al. 2007 (82)</td>
<td>Bacterial leakage</td>
<td>80</td>
<td>9 weeks</td>
</tr>
<tr>
<td>Kokorikos et al. 2009 (71)</td>
<td>Fluid filtration</td>
<td>98</td>
<td>1 year</td>
</tr>
<tr>
<td>Tay et al. 2005 (85)</td>
<td>Dye leakage</td>
<td>24</td>
<td>3 hours</td>
</tr>
<tr>
<td>Pitout et al. 2006 (96)</td>
<td>Bacterial and dye leakage</td>
<td>110</td>
<td>Bacterial: 3 months, dye: 72 hours</td>
</tr>
</tbody>
</table>

*In this study, the two filling materials showed similar coronal seal, but Resilon had a significantly better apical seal than gutta percha
The contradictory results from leakage studies may be attributed to differences in the study design: the type of tooth, the type of sealer used with gutta percha, time allowed for setting of sealer, method of leakage evaluation and concentration of sodium hypochlorite (NaOCl) used for irrigation. Different concentrations of NaOCl have been used (0.5% to 5.25%). It was reported that 5.25% NaOCl caused a significant reduction in flexural strength and modulus of elasticity of dentine in comparison with saline and 0.5% NaOCl (97). This may have a negative effect on the bond strength and leakage resistance of the filling materials. A study by Kececi et al. (88) used two different methods of assessment: glucose penetration and fluid filtration tests. Although the same samples were examined by both techniques and gave quantitative measurements, the results were different, as previously explained.

1.4.4 Ability of Resilon to reinforce root canal treated teeth in comparison with gutta percha

Root fracture is a commonly cited cause of endodontic treatment failure (98). Root canal treated teeth may be more susceptible to fracture because of a reduction in the amount of remaining tooth structure. Root canal treatment inherently requires removal of tooth structure to create straight line access and to permit thorough cleaning and shaping of the root canal system (99).

The strength of a root canal treated tooth is directly proportional to the quantity and quality of remaining tooth structure. The possibility for tooth fracture increases as tooth structure is removed (100). It was found that root canal preparation alone decreased tooth stiffness by only 5%, whereas the removal of coronal tooth structure in a mesio-occluso-distal (MOD) cavity reduced tooth stiffness by 60% (101). Gutmann (102) showed that dentine dehydration and alteration in collagen cross-
linking in root canal treated teeth resulted in a 14% drop in strength and toughness. Adding to these changes the forces that are applied during obturation, the potential for fracture of root canal treated teeth is real.

The resistance to fracture of endodontically treated teeth filled with Resilon was compared with those filled with gutta percha/AH-26 (18). Two techniques of obturation were used: cold lateral condensation and a continuous wave compaction technique. A loading fixture with a rounded end (2 mm in diameter) was applied along the long axis of the root at the canal orifice using a Universal Testing Machine. The results showed that root canals filled with Resilon had significantly higher fracture load values than those filled with gutta-percha regardless of the technique of obturation. Similar results were shown by other subsequent studies (103-105). There was no significant difference in fracture resistance between roots filled using cold lateral condensation and those filled using a continuous wave compaction technique with both materials. The mode of fracture in most of the roots was in a bucco-lingual direction, a finding which was also reported by Hammad et al. (104) in their study.

A different methodology was used in the studies by Teixeira et al. (18) and Hammad et al. (104). In the study by Hammad et al. (104), the full length of root was surrounded by a silicon tubing to resemble the periodontal tissues, and was then embedded in resin. In the study by Teixeira et al. (18), 9 mm of the coronal part of the roots were exposed and there was no silicone tubing. The vertical force in the study by Hammad et al. (104) study was applied using a sharp spreader inserted into the canal orifice at a speed of 10 mm/minute, whereas in the study by Teixeira et al. (18) it was applied using a loading fixture with a spherical end at a speed of 1
mm/minute. Despite these differences in methodology, both studies showed similar results.

In contrast to the studies by Hammad et al. (104) and Teixeira et al. (18), Ulosoy et al. (106), who used a methodology similar to that used in the study by Teixeira et al. (18), reported that the Resilon group showed significantly lower fracture loads than gutta percha/AH-26 sealer group. This result was also reported by Hanada et al. (107) when a vertical force was applied at the centre of the filling material using a rod with a flat end. In the latter study, it was observed that roots which were prepared to a master apical file (MAF) of size 80 had significantly lower fracture resistance than those prepared to an MAF of size 40. This finding highlighted the importance of the retaining dentine thickness to improve the fracture resistance of root canal treated teeth.

On the other hand, other studies (108-113) showed no significant difference in reinforcing root canal treated teeth between the Resilon and gutta percha/epoxy resin-based sealer. Nagas et al. (110) also investigated the effect of intra-orifice filling on fracture resistance. It was found that placing 3 mm of resin-modified glass ionomer or fibre-reinforced composite in the root canal orifice significantly improved the fracture resistance.

Wilkinson et al. (114) evaluated the resistance to cervical fracture of extracted immature sheep incisors filled with Resilon, a hybrid composite, a flowable composite or gutta percha/AH Plus sealer. The apical part of the root was restored with mineral trioxide aggregate (MTA) to create an apical plug and then backfilled with one of the tested materials (using a thermo-plasticised injection technique in the Resilon and gutta percha groups). The roots were then subjected to forces
perpendicular to the long axis at the cement-enamel junction (CEJ) using a sharp tip in a Universal Testing Machine. The lowest resistance to fracture was showed by the gutta percha group and the highest was exhibited by the hybrid composite group. A significant difference was found only between the gutta percha and the hybrid composite groups. The Resilon group showed higher fracture loads than those of gutta percha, but this was not statistically significant.

Another study by Stuart et al. (115) investigated the effect of the same materials used in the study by Wilkinson et al. (114) in reinforcing simulated immature human canines and premolars. The force was applied at 130° to the long axis of the tooth at the CEJ using a sharp tip in a Universal Testing Machine. Although the flowable composite group showed the highest mean values of forces required for cervical fracture, it was not significantly different from other filling materials. This is in agreement with Hemalatha et al. (116).

1.4.5 Bond strength of Resilon in comparison with gutta percha

The modulus of elasticity of dentine is about 16,000 megapascals (MPa) (117). In order to prevent debonding of composite resin as a result of stress concentration at the interface with dentine, the composite material should have a modulus of elasticity similar to that of dentine. Composites that are highly filled (70-80 volume %) have moduli of elasticity similar to dentine (12,000-16,000 MPa). As gutta-percha, whose modulus of elasticity is only 77 MPa, does not bond to dentine, it cannot strengthen root canal treated teeth. It was suggested that Resilon, which bonds to the root canal dentine, may have the ability to reinforce root canal treated
teeth (25). This claim has been investigated by many studies which showed conflicting results.

The cohesive strength and stiffness of Resilon and gutta percha was compared under dry conditions and after one month water storage to verify if they have the ability to reinforce roots (25). Twenty specimens of each material were prepared using a dog-bone shaped mould. Ten dry specimens were pulled to failure. The other ten were stored in water at 37°C for one month then they were subjected to the same test to which the dry samples were subjected to. The results showed that the cohesive strength and stiffness of both materials are relatively low. The modulus of elasticity of Resilon under dry conditions was 86.58 MPa which is far below that of dentine. Therefore, the ability of Resilon to strengthen endodontically treated roots was questioned. This is in agreement with a study by Grande et al. (118) who reported that the flexural strength and flexural modulus of gutta percha and Resilon are too low to strengthen root canal treated teeth.

Gesi et al. (119) evaluated the interfacial strength and displacement resistance between Resilon/Epiphany and intra-radicular dentine and compared them to those of gutta percha/AH Plus using thin-slice push-out tests as a reflection of the ability of the filling to strengthen the roots. Both materials showed low interfacial strengths. This result challenges the concept of reinforcement of roots filled with Resilon. An SEM was then used for examination of the failed slices. It was observed that slices in gutta percha group failed exclusively at the gutta percha-sealer interface, whereas Resilon slices detached along the sealer-dentine interface with presence of fractured resin tags. In some Resilon slices, unexpectedly, dislocation occurred at the Resilon-Epiphany interface. This was explained by the low concentration of dimethacrylate
in the Resilon matrix which is the part that is involved in bonding to the Epiphany sealer.

On the other hand, Skidmore et al. (120) reported that the bond strength in roots filled with Resilon was significantly higher than those filled with gutta percha/Kerr Pulp Canal sealer. This was also shown by Onay et al. (121). In the study by Skidmore et al. (120), the roots were cross-sectioned and slices from the coronal and middle thirds were used to measure the push-out bond strength using a Universal Testing Machine. The mode of failure was inspected using an SEM and this showed that dislodgment occurred predominately along the sealer-dentine interface in both groups. The sealer that was used in this study was Kerr Pulp Canal Sealer (a zinc-oxide/eugenol based sealer), whereas in the study by Gesi et al. (119), AH Plus was used (an epoxy resin-based sealer). It was reported that zinc-oxide/eugenol based sealers had lower bond strength to dentine than epoxy resin-based sealers (122). Therefore, this may explain the contradictory results obtained from the two studies despite their similar methodology. Another explanation is that the coronal surface in the Resilon groups in the Gesi et al. study (119) was light cured for 40 seconds which resulted in rapid polymerisation and restricted stress relief by resin flow leading to interfacial stress concentration and debonding.

In contrast to the study by Skidmore et al. (120), Shokouhinejad et al. (123), Ureyen Kaya et al. (124), De-Deus et al. (125), Sly et al. (126) and Fisher et al. (127) all reported that Resilon showed significantly lower bond strength than gutta percha combined with AH-26, AH Plus, Ketac-Endo (glass ionomer-based) or Epiphany sealers. Shokouhinejad et al. (128) reported that the bond strength of Resilon was not affected by irrigation with 5.25% NaOCl + EDTA or 1.3% NaOCl + MTAD. When
irrigation with 5.25% NaOCl + EDTA was used, gutta percha/AH-26 showed significantly higher bond strength than all of the other groups.

Ungor et al. (129) compared the bond strength of Resilon/Epiphany, gutta percha/AH Plus, Resilon/AH Plus and gutta percha/Epiphany using push-out tests. The bond strength of gutta percha/Epiphany was significantly higher than all of the other groups. Resilon/Epiphany showed no significant difference from gutta percha/AH Plus. Examination of the failed sections using a stereomicroscope revealed that the failure was mainly adhesive (at the sealer-dentine interface).

1.4.6 Clinical outcome after obturation with Resilon in comparison with gutta percha

Few studies have investigated the clinical outcome of teeth obturated with Resilon (20, 130, 131). Conner et al. (130) and Pawinska et al. (20) reported only on the outcome of endodontic treatment of teeth obturated with Resilon/Epiphany without comparing it to gutta percha. To date, there is only one study which compared the clinical outcome of endodontic treatment using Resilon to that of gutta percha (131).

The study evaluated clinical symptoms and assessed immediate and recall radiographs (at 12-25 months) using the Periapical Index (PAI); a 5-point scale in which 1 represents teeth with healthy apical periodontium, and 5 indicates the presence of radiolucency and radiating expansion of bony structures (132). The results indicated that the two obturation materials had no significant difference in the clinical outcome.

Conner et al. (130) investigated the clinical outcome of root canal treatment of teeth obturated with Resilon. Immediate post-operative radiographs were compared to
radiographs at one-year follow up. Two evaluation methods were used to determine the healing rate: the PAI and the Clinical Impression of Healing (CIH) where the observed teeth received one of three ratings: healed, healing or not healed/not healing according to a direct visual comparison between the immediate post-operative and follow-up radiographs. It was found that the healing rates of Resilon-filled teeth were within the range of success rate of endodontic treatment using gutta percha reported in the literature. In this study, there was no clinical assessment and the review period was relatively short.

Pawińska et al. (20) carried out a case-series study which investigated the outcome of endodontic treatment using Resilon as a root filling material. Clinical examination and radiographic assessment were performed immediately after the treatment and then at 6 and 12 months recall. It was concluded that Resilon yielded a positive treatment outcome. However, this study was preliminary with a limited number of teeth treated and reviewed for a short period of time.

1.5 Adhesion to dentine

The use of bonded resin materials has been restricted to restorative dentistry. Recently, adhesive materials have been introduced in endodontic treatment in an attempt to improve both the coronal and apical seal (30). Bonding to dentine involves the use of etching agents to enable hydrophobic materials to attach to the dentine surface. During the etching procedure, the smear layer is removed, dentine is demineralised and the collagen matrix is exposed. Then a primer, which is a monomer incorporated in a volatile carrier, such as acetone or alcohol, is applied to the etched dentine surface. The carrier infiltrates the demineralised dentine and
carries the primer into the exposed dentinal tubules and collagen matrix. Air dryness of the dentine evaporates the volatile carrier leaving the resinous material behind (30).

The next step is the application of an adhesive, which is an unfilled or lightly filled resin, to the dentine surface and light curing. The adhesive co-polymerises with the resin which has infiltrated the collagen matrix and dentinal tubules. The resin which has penetrated the dentinal tubules forms “resin tags”. The layer of the collagen matrix infiltrated by resin material is referred to as the “hybrid layer” which is 2-5 \( \mu \text{m} \) in thickness (30).

A hydrophobic resin material can be bonded to dentine by the process of hybridisation. Contrary to the common belief, resin tags have only a minor role in dentine adhesion, about 15%. It was found that the micromechanical retention given by the hybrid layer in the inter-tubular dentine contributes to the bond strength more than the resin tags (133).

Dentine bonding was first explained by Nakabayashi et al. in 1982 (30). The procedure involved three steps: etching and rinsing, priming, and adhesion. To simplify the bonding procedure, two-step etch-and-rinse, two-step self-etch and one-step self-etch bonding have been introduced (Figure 1.1) (134). However, the bond strength resulting from these simplified processes has been shown to be less than that created by three-step total etch adhesives (135).
1.5.1 The concept of monoblock

The term “Monoblock” means that the root filling material and the root canal wall chemically adhere to each other forming a single unit (136). There are two requirements for a successful monoblock. First, the materials that form a monoblock should have the ability to bond to one another, as well as to the substrate. Second, the modulus of elasticity of the materials should be similar to that of the substrate (136). Monoblocks formed in root canal spaces are classified as primary, secondary or tertiary depending on the number of interfaces between the substrate and the core material (Figure 1.2) (136).
1.5.1.1 Primary monoblocks

A primary monoblock is created when there is only one interface that extends circumferentially between the material and the root canal wall (136).

1.5.1.2 Secondary monoblocks

A secondary monoblock is formed when there are two circumferential interfaces, one between the sealer and dentine and the other between the sealer and the core material. This type of monoblock is classically perceived in contemporary endodontic obturations and fibre post adhesion (136).

1.5.1.3 Tertiary monoblocks

A tertiary monoblock is created when there is a third circumferential interface between the substrate and the core material. EndoRez system (gutta percha cones coated with resin) and ActiV GP (gutta percha cones coated with glass ionomer fillers) are considered as tertiary monoblocks. Fibre posts that have an external layer of either silicate or unpolymerised resin to provide proper fitting to the root canal are another example of tertiary monoblocks (136).
Figure 1.2 Classification of endodontic monoblocks (136)
1.5.2 Problems with dentine bonding

1.5.2.1 Polymerisation shrinkage

Polymerisation of resin materials is associated with shrinkage which results in forces that are often greater than the bond strength, leading to separation at the areas of weakest bond (134). This separation results in gaps through which micro-organisms can infiltrate and proliferate.

1.5.2.2 Configuration factor (C-factor)

The C-factor is the ratio of bonded to unbonded resin surface area (137). The greater the C-factor, the greater the stress is on the bonded surfaces from contraction forces. The unbonded surfaces allow relief of these forces. It was reported that a C-factor of less than three is favourable for bonding (138). In the root canal system, the C-factor may be more than 1000 (139) as there are few unbonded surfaces. Therefore, debonding is frequently detected along the dentine-sealer interface (139). The use of dual-cured sealers can provide more time for stress relief via resin flow (140).

1.5.2.3 Time factor

Weakening of the bond strength with time was observed in a number of studies (134, 141). There are several factors which lead to deterioration of the bond strength: microleakage (142), nanoleakage, biodegradation of the hybrid layer (143), non-polymerised resin and functional stress (134). If a resin material comes into contact with fluids, plasticisation occurs. Plasticisation is a condition in which the resin material absorbs fluids and swells leading to deterioration in its mechanical
properties. Furthermore, contact with fluids can cause hydrolysis of the resin material.

Biodegradation of hybrid layers was hypothesised to occur in a cascade of events (143). The first stage begins during acid etching of the dentine to remove the smear layer and expose the underlying collagen fibres. In the second stage, resins that had penetrated the dentine matrix through water-filled channels within the hybrid layer are extracted. During the third stage, collagen fibres are attacked by enzymes such as esterases and matrix metalloproteinases (MMPs). To avoid such biodegradation, total penetration and curing of resins are essential. In addition, blocking the action of the enzymes at the resin-dentin interface might be required. Although acid-etching reduces the collagenolytic activity of the enzymes, some residual action remains. Even more reduction in the enzymatic activity occurs when the collagen fibres, to which the MMPs are attached, are infiltrated by the resin. However, if the collagen fibres are inadequately infiltrated by the resin, or if resin hydrolysis occurs, MMP activity can be recovered (144). Hashimoto et al. (145) reported that the activity of MMPs could be inhibited by chlorhexidine. If chlorhexidine could be incorporated into etchants, primers or adhesives, it might preserve the durability of the resin-dentine bond.

Simplified adhesives were reported to have more bond deterioration than three-step etch-and-rinse adhesives (134). Since weakening of the bond strength was first observed at three months (134), all clinical studies of bonding should be more than three months to be valid (30).

The depth of penetration of resin into the demineralised dentine is an important factor for the stability and strength of the bond. Over-etching may result in deeply
demineralised dentine that cannot be fully infiltrated by the resin material. Incomplete infiltration results in passage of fluids between the hybrid layer and the unaltered dentine. This is called “nanoleakage” because it occurs through spaces that are only 20-100 nm wide, whereas spaces that permit microleakage are 10-20 \( \mu \)m wide (143). Nanoleakage may lead to faster bond deterioration (134). It can also occur as a result of the presence of residual water at the dentine-resin interface.

1.5.2.4 Structure of radicular dentine

The apical one-third of the root contains fewer dentinal tubules than the coronal dentine (146) and, as a result, fewer resin tags are formed during the adhesion procedure. Since it has been reported that the hybrid layer contributes more to the bond strength than resin tags (133), radicular dentine can be considered more favourable for bonding as it contains more intertubular dentine for hybrid layer formation (147).

Studies have shown conflicting results about the bond strength in the apical one-third of the root compared to the middle and coronal thirds. Some studies revealed higher bond strengths (148, 149), some lower bond strengths (150, 151) and others slight variation (152, 153).

1.5.2.5 Bonding to deep areas in the root canal system

The application of adhesive materials in deep parts of the root canal can be very challenging. Improper drying of the root canal walls may leave water droplets that may become entrapped within the adhesive material and act as crack propagation areas (136). This occurs due to the formation of “water trees” as described by Tay
and Pashley (154) to reflect the similar appearance of water trees that occur in the insulating material around underground electrical cables. These are microscopic tree-like water channels that project from the surface of the hybrid layer extending through the adhesive layer to reach the interface between the adhesive and Resilon. Water-trees were detected when the resin-dentine interface was stained with a silver nitrate tracer and examined using an SEM. The formation of these water channels in the polymerised adhesive material provides pathways for the movement of water across the interface with the dentine leading to hydrolytic degradation of the bond (154).

For successful bonding, the primer must be placed accurately on the dentine wall. This may not be possible in the apical area of the root canal. The use of compressed air to dry the primer may result in subcutaneous emphysema (155). Paper points may not eliminate the volatile carrier part of the primer properly which may have a negative effect on the bond (156).

1.5.2.6 The effect of medicaments and irrigation solution used in endodontic treatment

The most commonly used irrigant solution in endodontic treatment is NaOCl, which is a strong oxidizing agent. Oxygen remaining on the root canal walls can cause a reduction in bond strength (157, 158), inhibition of resin polymerisation (158) and an increase in microleakage (159). The same effect may occur if hydrogen peroxide is used (160). To overcome this problem, a reducing substance, such as ascorbic acid or sodium ascorbate, may be used after NaOCl to neutralise its effect. It has been reported that the bond strength returned to its original level following the application of these reducing agents (157). Alternatively, a non-oxidising irrigant, such as
chlorhexidine, can be used as an irrigant if the root canal is to be obturated with an adhesive filling material.

Several materials containing eugenol are used in root canal treatment as sealers and temporary filling materials. Eugenol can interfere with the polymerisation of resin material (161). The root canal should be cleaned mechanically and a three-step etch-and-rinse adhesive system should be used to remove any eugenol that may have adhered to the dentine wall or got incorporated in the smear layer (30).

Calcium hydroxide is frequently used as an inter-appointment medicament. Complete removal of calcium hydroxide may not be possible and this may also interfere with successful bonding to dentine by acting as a barrier and also neutralising the acidic primer in self-etching adhesive systems (30).

### 1.5.3 The effect of the smear layer

Instrumented root canal surfaces are covered with a layer composed of organic and inorganic material and may contain micro-organisms (162). This layer is the smear layer which was first identified by Eick et al. (163) using scanning electron microscopy. It extends few micrometres into the dentinal tubules forming dentine plugs and is not present on unprepared surfaces. Removal of the smear layer before obturation has been a subject of a long debate.

Safavi et al. (164) suggested that the smear layer should be maintained to restrict penetration of micro-organisms and their toxins into the dentinal tubules. Micro-organisms remaining after preparation of the root canal may be entombed into the
dentinal tubules by the smear layer. It was reported that removal of the smear layer caused a significant increase in apical leakage (165).

On the other hand, other authors support its removal for many reasons. Meryon and Brook (166) explained that the smear layer harbours micro-organisms which can survive, proliferate and compromise the outcome of endodontic treatment. The organic components of the smear layer may serve as a substrate for micro-organisms (167). Its loose attachment to the dentine walls and its degradation by micro-organisms can create an avenue through which leakage may occur (166).

Effective disinfection of the root canal walls and dentinal tubules may be limited by the presence of the smear layer (168). However, Ørstavik and Haapasalo (169) reported that the action of disinfectants during root canal preparation was delayed and not totally abolished when the smear layer was not removed.

The smear layer may act as a barrier against proper adaptation of the filling material to the root canal walls (170). Okşan et al. (171) reported that the smear layer interfered with penetration of the sealer into the dentinal tubules. Removal of the smear layer was reported to decrease coronal leakage (172). However, Saleh et al. (69) reported that removal of the smear layer did not improve leakage resistance.

The current recommendation is to remove the smear layer before obturation (162). Removal of the smear layer can be performed by the alternative use of NaOCl, which dissolves the organic components of the smear layer, and a chelating agent which remove the inorganic components (173). The chelating agents which have been used are EDTA, the most commonly used, MTAD and citric acid. As NaOCl was found to be deactivated by EDTA and citric acid, it is recommended that NaOCl
is used throughout root canal preparation and then a final rinse of EDTA or citric acid is applied (173). Ultrasonic instruments combined with NaOCl can also be used for removal of the smear layer (162).

1.6 Homogeneity of the root filling using cold lateral condensation or thermal obturation techniques

Following thorough cleaning of the root canal, a three dimensional seal of the root canal system should be achieved (7). The filling material should be homogenous with no voids that may permit leakage of micro-organisms or fluids. One of the potential drawbacks of cold lateral condensation is that it relatively poorly replicates the root canal surface and tends to form voids and spreader tracts between gutta percha points (174).

Wu et al. (175) investigated the percentage of gutta percha-filled canal area in mandibular premolars obturated using cold lateral condensation or warm vertical compaction (175). The obturated roots were cross sectioned at 2 and 4 mm from the apex. Using a microscope, images were obtained and analysed. The study showed that the warm vertical compaction group had a significantly higher percentage of gutta percha-filled canal areas than the cold lateral condensation group. This finding was consistent with the results obtained by Kandaswamy et al. (176) and Anbu et al. (177). Spiral CT was used in the studies by Kandaswamy et al. (176) and Anbu et al. (177) to evaluate the volume of the filling material.

Epley et al. (42) evaluated the completeness of obturation of root canals filled with gutta percha/Roth sealer (zinc-oxide/eugenol based) or Resilon/Epiphany sealer inserted into the canal using cold lateral condensation or continuous wave
compaction techniques. The roots were horizontally sectioned at three levels (1, 3 and 5 mm from the apex) and digitally photographed using a stereomicroscope. The images were then analysed using software to measure the surface area of the voids. The results showed that, at one of the three tested levels (3 mm from the apex), the gutta percha/cold lateral condensation group had significantly more voids than the other groups. No significant difference was found between the groups at the other tested levels.

The homogeneity of root canal fillings carried out by undergraduate dental students using cold lateral condensation and warm vertical compaction techniques in simulated root canals was investigated (178). Digital radiographs were taken in two projections and the images were analysed. The plastic blocks were then sectioned and examined using a light microscope. Both assessment methods showed that warm vertical compaction resulted in a more homogenous filling with significantly fewer voids than cold lateral condensation. This agrees with the previously mentioned studies by Epley et al. (42), Kandaswamy et al. (176) and Wu et al. (175). On the other hand, a study by Keçeci et al. (179) showed no significant difference in the area of voids and filling material between the two techniques of obturation.

The percentage of obturated volume was investigated in teeth filled with gutta percha and AH plus sealer using different obturation techniques (177). Four techniques were compared: cold lateral condensation, Thermafil, Obtura II and System B. Spiral CT was used to measure the obturated volume in each canal. The results showed that System B and Thermafil resulted in the highest percentage of obturated volume which was significantly higher than Obtura II and lateral compaction. The latter
technique showed the least percentage of obturated volume. All fillings in this study contained some voids.

1.7 Methods of assessment of quality of obturation

Assessment of the quality of obturation has been carried out using various methods such as radiographs (178), sectioning the roots and examining the filling using a stereomicroscope (40, 42, 175, 179), scanning electron microscopy (39), dye leakage tests (58), radioactive isotopes tests (180), electrochemical tests (181, 182), fluid filtration testing (175), bacterial leakage testing (48), and glucose leakage testing (76), a split-tooth model (44), computed tomography (CT) (176, 177) or micro-CT (41).

Radiographs are not reliable as they give a two-dimensional view of the filled tooth and therefore, superimposed structures can make it difficult to detect voids in the filling material. Sectioning the roots, which was the most commonly used technique for void detection, may result in removal of some of the filling material which may appear like voids (177).

Microbial leakage studies may be more biologically relevant than dye and radioisotopes tests, but they do not give quantitative measurements of leakage and require long observation periods (11). In addition, it may be difficult to maintain an aseptic environment throughout the test and the results may vary according to the bacterial species used (183).

Radioisotope and electrochemical methods are less frequently used because they involve a radiation hazard and require complicated equipment (183). The glucose
filtration test was introduced by Xu et al. (183). Glucose was used as a tracer because it has a small molecular size and is a nutrient for bacteria. Xu et al. (183) suggested that if glucose could pass through the filled root canal from the oral cavity, residual bacteria could proliferate and eventually cause periapical inflammation. Therefore, it was thought that glucose might be more clinically relevant than other tracers. In this method, quantitative measurement of leakage of glucose was carried out using spectrophotometry.

The dye leakage method is the most popular method in evaluation of leakage (183). Different dyes have been used such as methylene blue dye (63), India ink (91) and ammoniacal silver nitrate (85). Air entrapped in the voids, when not performed under reduced air pressure, may interfere with the penetration of the dye resulting in a failure to reveal the actual size of the voids (184). However, other studies (185, 186) reported that the application of a vacuum before dye penetration had a little or no effect on the extent of dye penetration. It was reported that when the dye comes in contact with some filling materials, its colour may be lost (187).

The amount of dye leakage is evaluated by one of two methods. Clearing the roots and measuring the linear extent of the dye penetration using a stereomicroscope is one method (54, 55). The other method is by cross-sectioning the roots and examining them using a stereomicroscope to confirm the presence or absence of leakage (58) or longitudinal-sectioning and measuring the extent of dye penetration using a stereomicroscope (57). A new dye penetration assessment method was introduced by Ishimura et al. (93) which permitted quantitative measurements of leakage. In this method, a spectrophotometer was used to measure the concentration of the dye passed through the obturated root and released into water.
The fluid filtration method, which was developed by Derkson et al. (188) and modified later by Wu et al. (189) and Abramovitz et al. (190), can be time consuming. However, it was shown to have advantages over other leakage tests:

- It allows quantitative measurements of fluid percolation through the filled canals.
- It does not require tracers, therefore avoiding problems related to affinity to dentine and molecular size.
- Samples are kept intact which allows repeated measurements over a course of time.
- It does not require a special material such as in the dye, glucose or bacterial penetration tests.

The use of micro-CT in endodontic research has recently increased. Its main advantage is that the root canal system can be visualised without destroying the samples. It has been used to understand root canal morphology, evaluate the effect of instrumentation on root canal shape and assess the quality of obturation materials and techniques. More details about micro-CT are presented in Chapter 3.
1.8 Causes of failure of endodontic treatment

Endodontic treatment often fails when it is performed below accepted standards. The implications of micro-organisms in pulpal and periapical diseases are well documented (5). Periapical disease may persist or emerge following completion of root canal treatment as a result of intra-radicular infection, extra-radicular infection or non-microbial factors (191).

The main cause of failure is persistent or recurrent microbial infection (192, 193). It was reported that some parts of the root canal system may remain untouched during endodontic disinfection procedures (194, 195). Additionally, procedural errors such as ledges, perforations or instrument separation may impede proper chemomechanical cleaning (196). Untreated canals may contain necrotic tissues and microorganisms. Residual micro-organisms may be entombed by the filling material and eventually die. However, some may get nutrients from seepage of tissue fluids if the obturation material does not provide a fluid-tight seal. Subsequently, these micro-organisms can proliferate and gain access to the periapical tissues leading to continuation or emergence of periapical inflammation (191).

The root canal system may be re-contaminated after endodontic treatment via coronal leakage and this has been reported to be an important cause of failure of endodontic treatment. This leakage may occur due to number of causes (10):

- Delay in providing a permanent coronal restoration. Temporary filling materials have accepted sealing properties. However, they dissolve in oral fluids and therefore may allow leakage over time.
- Breakage of the coronal restoration and/or tooth.
- Recurrent caries that causes exposure of the root filling material.
- Leaving an apical root canal filling of insufficient length and/or density when preparing a post space.

It has been demonstrated that oral bacteria can penetrate the entire obturated root canal system that had been exposed coronally within a period of less than 30 days (197). Therefore, root canal treated teeth that have been exposed coronally for 30 days or more should be retreated (191).

Extra-radicular infection may also be implicated in post-treatment disease. Contaminated instruments or dentine debris may be pushed into the periapical tissues during instrumentation and result in persistent periapical infection (198). Overextension of filling materials has been reported to negatively affect the prognosis of endodontic treatment specifically in teeth with pre-operative periapical periodontitis (199). Impairment in prognosis may be attributed to the over-instrumentation and contamination of the periapical tissues rather than the filling materials per se (199, 200). Failure of endodontic treatment has also been attributed to non-microbial factors such as a foreign body reaction or a periapical cyst (201).

Extra-radicular infection and non-microbial factors do not respond to non-surgical retreatment. As the cause of treatment failure is usually made after surgical treatment, it is recommended to retreat failed endodontically treated teeth before surgical intervention to exclude the most common cause of failure which is intra-radicular infection (191).
1.9 Non-surgical retreatment

Non-surgical retreatment is usually the preferred initial choice in treating failed endodontically treated teeth as it has a greater chance to eliminate any intra-radicular infection than surgical retreatment (202). It comprises removal of the old root filling material to allow access to any residual micro-organisms and permit further cleaning and disinfection of the root canal system (203). Efficient removal of previous filling materials can ensure intimate contact between the sealer and the root canal walls to prevent leakage of micro-organisms (204). Until now, it has not been confirmed that incomplete removal of root filling materials will result in the failure of retreatment. However, the effective removal of root filling materials would appear to be crucial in order to expose any residual micro-organisms that may be responsible for post-treatment disease (205).

1.9.1 Removal of root filling materials

Several techniques have been used to remove existing filling materials from root canals such as hand files, nickel-titanium (NiTi) engine-driven files or ultrasonic instruments with or without the adjunctive use of solvents or heat. The use of hand files can be a very tiresome and time-consuming procedure, especially if the filling material is well-condensed (206). Therefore, a combination of two or more techniques may be more effective and time-saving (207). Furthermore, it is recommended to use a technique of preparation that is different from the one used in the first or any subsequent retreatment in order to improve cleaning and therefore success rate. It was reported that if the same technique of preparation was used, it was unlikely that uncleaned areas would be reached and cleaned on the second
treatment (208). It was suggested that during retreatment, root canal preparation should be performed to a size larger than the last one used in the previous treatment in order to reduce the amount of residual material (209-211).

1.9.2 Comparison between different techniques in removal of gutta percha and Resilon

Despite the high success rate in endodontic treatment, cases do fail and require retreatment. During this procedure, the old root filling material is removed to allow disinfection, cleaning and refilling of the root canal system. Different materials used in filling root canals can be encountered during retreatment and have different removability.

To date, the literature has not reported which removal technique is the most effective. However, most studies agree that no technique results in complete removal of the root filling material (21, 206, 207, 209, 212-216). Different removal techniques of filling materials have been investigated and compared with respect to two main aspects: effectiveness and time required for removal.

Several studies have demonstrated the effectiveness of NiTi rotary instruments in removal of filling materials from the root canal (207, 213, 217). Their use can reduce patient and operator fatigue (218). On the other hand, there is a higher risk of instrument fracture than using hand files (214).

Duarte et al. (219) evaluated the efficacy of K-hand files and ProTaper Universal rotary files in the removal of a root canal filling after periods of storage of one week or six years. Root canals were filled with gutta percha/Endofill (zinc-oxide eugenol-based sealer) and were stored in saline. Following removal of the filling material,
digital radiographs were taken and the roots were split longitudinally and examined using a clinical microscope. Digital images were obtained and analysed. The results showed no significant difference between the two removal techniques, irrespective of the age of the filling. This is in agreement with studies by Fenoul et al. (220), Barrieshi-Nusair (221) and Gergi and Sabbagh (222), but contradicts studies by de Carvalho Maciel and Zaccaro Scelza (223) and Saad et al. (224) which reported superior effectiveness with rotary instruments. On the other hand, Hammad et al. (21) showed that hand K-files removed gutta percha more effectively than ProTaper retreatment files.

In the study by Duarte et al. (219), it was observed that removal of a one-week-old root filling resulted in significantly more residue in the middle third of the root canal than with a 6-year-old filling. This was explained by the presence of stronger adhesion between the sealer and the root canal walls in the one-week-old filling. The other two-thirds of the root canal showed no significant difference in remaining material. This was attributed to the circular cross-section of the apical third that enabled better contact of instruments with the root canal wall. In the coronal third, the straight line access assisted material removal. However, when comparison was made between root canal thirds, the apical third showed significantly more remnants than the other two thirds in both groups. This was consistent with studies by Masiero and Barletta (213), Gergi and Sabbagh (222), Somma et al. (215), Hassanloo et al. (209) and Fenoul et al. (220).

Schirrmeister et al. (205) compared the effectiveness of Hedstrom hand files and RaCe rotary files in the removal of gutta percha and Resilon without the use of any solvent. The filling materials were removed after one week of storage. The roots
were then cleared and digital images were obtained using a stereomicroscope. Analysis of the images showed significantly more gutta percha remained than Resilon, regardless of the instruments used for removal. This agrees with studies by Hammad et al. (21) Cunha et al. (225), Bodrumlu et al. (226), Pinto de Oliveira et al. (207) and Marfisi et al. (216), but contradicts studies by Zarei et al. (227) and Hassanloo et al. (209) which reported that removal of Resilon resulted in significantly more residual material than gutta percha. On the other hand, a study by Fenoul et al. (220) reported no significant difference in removability between Resilon and gutta percha.

Although the use of RaCe rotary instruments in the study by Schirrmeister et al. (205) resulted in less remaining material than Hedstrom files, this was not statistically significant. By contrast, Schirrmeister et al. (214), using the same method of assessment, reported that RaCe rotary files resulted in significantly cleaner canal walls than Hedstrom hand files and FlexMaster files. In the study by Schirrmeister et al. (205), there was no significant difference in time required for removal of Resilon and gutta percha using either method of removal. However, Hedstrom files removed both materials significantly faster than RaCe instruments. This was contradictory to the study by Schirrmeister et al. (214) which showed Race to be faster than Hedstrom files.

Pinto de Oliveira et al. (207) investigated the effectiveness of K3 and Liberator rotary instruments with chloroform in removal of gutta percha/AH-26 and Resilon. Following two weeks of storage, the filling materials were removed. The roots were split vertically and imaged using a digital camera. The results showed that the K3 rotary system removed gutta percha/AH-26 and Resilon/Epiphany more effectively.
than Liberator rotary files. Roots obturated with Resilon/Epiphany and retreated with K3 files showed significantly less remaining material than gutta percha groups retreated with either files. Resilon/Epiphany was removed faster than gutta percha/AH-26 using either file systems. This is in agreement with studies by Ezzie et al. (228) and Bodrumlu et al. (229), but disagrees with studies by Schirrmeister et al. (205) and Marfisi et al. (216) which reported no significant difference in the time of removal of Resilon and gutta percha.

Marfisi et al. (216) evaluated the efficacy of ProTaper retreatment files, Mtwo retreatment files and Twisted files in removal of gutta percha/AH Plus and Resilon. The filled roots were stored for two weeks before removal of the filling materials. Cone beam computed tomography (CBCT) was used to assess the remaining material. The roots were then sectioned vertically and examined using an optical microscope. No significant differences in residual material were observed between the instruments used for removal of the filling material. Nevertheless, Resilon was more effectively removed than gutta percha irrespective of which rotary files were used. Mtwo files removed filling materials significantly faster than the other two systems.

The efficacy of the combined use of chloroform and ProFile 0.06 rotary files in removal of gutta percha/AH Plus and Resilon was compared with the use of heat and ProFile 0.06 (228). The obturated roots were stored for three weeks before removal of the filling materials. Examination of the remaining material was carried out by sectioning the roots and using a stereomicroscope to obtain digital images for analysis. SEM was used to examine representative specimens. The results showed that the use of ProFile instruments with chloroform resulted in cleaner canal walls
than the use of the instruments with heat. The same finding was observed by the use of SEM. Resilon required significantly less time for removal and showed cleaner canal surfaces in the apical one-third than gutta percha regardless of the method of removal.

Hassanloo et al. (209) compared the effectiveness of removal of Resilon/Epiphany using K3 0.04 rotary files to that of gutta percha/AH Plus. After preparation of the root canals, the roots were embedded in resin blocks with fixation rods to help in reassembling. The roots were sectioned vertically and digital images were taken to be used as a baseline for the subsequent images. The roots were reassembled, filled with the filling materials and stored for eight weeks in an anaerobic incubator. Afterwards, the filling materials were removed with K3 rotary files either with or without chloroform. The roots were disassembled and examined using a dissecting microscope. The Resilon/Epiphany group showed significantly more residual material than the gutta percha/AH Plus group regardless of the method of removal. This agrees with a study by Zarei et al. (227), but contradicts other studies which showed less remaining material in roots filled with Resilon/Epiphany than those filled with gutta percha/AH Plus (21, 205, 207, 216, 225, 228). Residues were significantly more in the apical third than the middle and coronal thirds in all groups. In this study, it was reported that significantly less residual material was apparent when the root canals were instrumented to two sizes larger than the last size used in first treatment. Nonetheless, extensive apical enlargement can increase the risk of canal transportation and apical perforation.

In the study by Hassanloo et al. (209), retreatment time was significantly longer in roots obturated with Resilon/Epiphany than those filled with gutta percha/AH Plus.
This is in agreement with a study by Iizuka et al. (230), but is contrary to the studies by Ezzie et al. (228), Pinto de Oliveira et al. (207), which reported significantly shorter time required for Resilon removal than gutta percha. On the other hand, Cunha et al. (225), Schirrmeister et al. (205) found no significant difference in time for removal.

1.9.3 Possible reasons for the contrasting results in retreatment studies

The different results obtained in the study by Hassanloo et al. (209) may be explained by several differences in study design:

1.9.3.1 Time allowed for setting of the sealers

In the study by Hassanloo et al. (209), the Epiphany sealer was allowed to set for eight weeks in an anaerobic incubator, whereas in the studies by Pinto de Oliveira et al. (207), Ezzie et al. (228), Schirrmeister et al. (205) it was left to set for 1-3 weeks in an aerobic environment. It was reported that complete setting of the Epiphany sealer takes about 30 minutes in an anaerobic field, but in an aerobic environment it may take one week with a layer of unset sealer on the surface (231). Therefore, full setting of Epiphany sealer may be questioned in studies that did not allow enough time for sealer setting. If the sealer did not set completely, its removal would be relatively easier than with a set filling, and as a result fewer residues would be observed (209).
1.9.3.2 The use of Gates-Glidden drills

Gates-Glidden drills were used to remove only 2 mm of root canal filling in the study by Hassanloo et al. (209), while in the studies by Pinto de Oliveira et al. (207) and Cunha et al. (225) they were used to remove 5-6 mm of the filling material, thus leaving approximately 4-5 mm of apical filling. This amount of apical filling material may not be enough to compare effectiveness of retreatment techniques. Gates-Glidden drills would have removed some root canal dentine along with the filling material resulting in a clean root canal surface. Additionally, enlarging the coronal and middle thirds of the root canal would have assisted in removal of filling material in the apical third (209).

1.9.3.3 Technique of obturation

Cold lateral condensation was used to obturate the root canals in the study by Hassanloo et al. (209), while in the studies by Ezzie et al. (228) and Schirrmeister et al. (205) warm vertical compaction was used. The latter technique may require lesser amount of sealer than the former one. Hence, there would be lesser sealer to be eliminated.

1.9.3.4 The use of solvents

Chloroform was used only at the beginning of removal of the root filling material in the study by Hassanloo et al. (209), but it was placed several times in the root canal during retreatment in the studies by Ezzie et al. (228), Pinto de Oliveira et al. (207) and Cunha et al. (225). This would have facilitated removal of filling material and resulted in less remaining material.
1.10 Methods of assessment of residual filling materials

Several methods have been used to assess the effectiveness of removal of filling materials in endodontic retreatment such as radiographs and digital imaging (213, 219, 225, 232). These methods only give a two-dimensional image of a three-dimensional structure. The two-dimensional view gives inaccurate information as the root canal contents can superimpose.

Another method of assessment is longitudinal splitting of roots and viewing the remaining material using a stereomicroscope, obtaining digital images and analysing them with special software (207, 220, 226-228, 233, 234). Disadvantages of this method are that some material may be lost during sectioning of roots and it gives a two-dimensional image of the residual materials.

A clearing method has also been used in which the roots are made transparent and then the residual materials are imaged using a stereomicroscope. The images obtained are analysed using image analyser software (205, 214, 218). It was claimed that solutions used in this method had no influence on the remaining materials inside the root canals (214).

Recently, CT has gained increasing popularity in endodontic research (12, 41, 235). It creates a three-dimensional image of the root canal content without destroying the samples. Intact samples can then be used for further research. Micro-CT has also been used in endodontic research which creates images with much better resolution than CT (approximately 1,000,000 times smaller voxels) (236). Other features of micro-CT are discussed in Chapter 3.
Chapter 2

Statement of the Problem and Aims & Objectives
2.1 Statement of the problem

Following completion of chemo-mechanical preparation, the root canal system should be filled in three dimensions with a material that provides a fluid-tight seal. Gutta percha has been the filling material of choice for many years, but it has some limitations, most significantly of which is that it does not bond to any type of sealer (28). As many sealers shrink upon setting, gaps or voids may be created through which microleakage can occur (48, 49). Studies show that gutta percha is not capable of preventing leakage should the coronal seal fail (48, 49, 56) and the provision of a high quality coronal seal may be as important as the quality of gutta percha filling itself in prevention of re-infection of the root canal system (237).

A newly introduced resin-based material, Resilon (Pentron Corp., Wallingford, US), has been claimed to bond to the root canal dentine, strengthen the root (18, 104) and provide a better seal than gutta percha (48, 56). It has the same handling properties as gutta percha and can be placed into the root canals using cold lateral condensation (41, 64) or thermal methods (23, 42).

Properties of Resilon have been thoroughly investigated (18, 23, 32, 39, 41). However, most of the studies are related to its use in cold lateral condensation. As the use of thermal obturation is increasing (238), investigation of the quality of obturation with Resilon when it is placed into the canal using this method is timely. Few studies have been conducted using thermal obturation. Epley et al. (42) investigated the completeness of obturation in roots filled with Resilon in comparison with gutta percha using thermal and cold lateral condensation. In this
study, the filled roots were sectioned which may potentially lead to loss of some of the filling material and creation of a space that may mimic voids.

During endodontic procedures, several materials are used which may affect the bond between Resilon and the root canal dentine. It has been reported that 5% NaOCl (157), chlorhexidine (239) and CH (240) resulted in a reduction in the bond strength between Resilon and dentine. There has been no report on the effect of other medicaments, such as Vitapex and iodoform, on the bond of Resilon to dentine.

When endodontic retreatment is indicated, it is essential that the filling material can be effectively removed to permit access to any residual or re-introduced microorganisms (202). Many studies have been conducted to compare removability of Resilon in comparison with gutta percha (21, 205, 207, 209, 216, 225, 228). However, no study has investigated if there is a relation between the success of removal of these materials and the method of obturation (i.e. cold lateral condensation or thermal obturation). In addition, most of these studies compared the effectiveness of either rotary to hand instrumentation (21, 205) or compared different rotary systems (207, 216, 228). The use of hand instruments in combination with rotary files for effective removal of filling materials has been advocated (21), but no study has investigated the effectiveness of a combination.

Root treated teeth may become susceptible to fracture as a result of extensive loss of coronal tooth structure (101) and changes in physical properties of dentine (102). As gutta percha does not bond to the root canal dentine, it does not provide any resistance to fracture to the root canal treated teeth (25). The effect of Resilon in increasing resistance of root canal treated teeth to fracture has been investigated (18,
103, 104, 108, 110). All of these studies investigated Resilon in primary endodontic treatment. In retreatment, the roots are potentially even more susceptible to fracture as a result of further removal of dentine. Also, it is not known whether the technique used for removal of the filling materials have any effect on the fracture resistance of the root.

One of the important requirements of a root filling material is its ability to resist leakage and prevent re-infection of the root canal system (10). Several studies have compared the sealing ability of Resilon with that of gutta percha (48, 64, 65, 75). All of these studies investigated roots that had been filled with the tested materials as in primary endodontic treatment. After retreatment, any remaining material in the root canals may interfere with the bonding of Resilon to dentine and affect its leakage resistance. Investigation of the relation between the retreatment technique and the leakage resistance of the filling material is needed.
2.2 Aims and Objectives

The overall aim of this research is to investigate some of the properties of Resilon in primary and secondary endodontic treatment. The specific objectives are to:

- evaluate the three-dimensional quality of obturation with Resilon in comparison with gutta percha using either cold lateral condensation or continuous wave of compaction filling techniques.
- assess the effect of calcium hydroxide and its oil- and aqueous-based combinations with iodoform on the bond strength of Resilon to root canal dentine.
- investigate the effectiveness of the combined use of hand K-files and ProTaper retreatment files in removal of Resilon in comparison with gutta percha using micro-CT.
- investigate the fracture resistance of Resilon-refilled roots following retreatment using either hand K-files or ProTaper retreatment files.
- evaluate the leakage resistance of Resilon-refilled root canals following retreatment using either hand K-files or ProTaper retreatment files.

The outline of this thesis is illustrated by a flow chart in Figure 2.1. The use of extracted human teeth in this research was approved by the Ethics Committee at the University of Manchester (Figure 2.2).
Figure 2.1 A flow chart illustrates the outline of this thesis
Figure 2.2 An ethical approval letter for the use of extracted human teeth in this research
Chapter 3

Methodologies
3.1 Volume of voids and remaining material using Micro-computed Tomography (Micro-CT)

3.1.1 Introduction

The word tomography is a word derived from two Greek words: *tomos*, which means slice, and *graphein*, which means to write and is defined as “to draw a section of an object” (241). Computed tomography (CT) imaging was initially developed in the early 1970s. It is based on similar technology to that used in dental radiography. However, rather than taking just one 2D radiograph, the tooth is rotated through 360° during which time it is exposed to radiation. Generally, over 1000 images are collected per scan. The series of radiographs is then used to reconstruct a 3D image (242).

Clinical CT scanners construct images composed of 1 mm$^3$ volume elements (voxels), whereas micro-CT scanners, introduced in the early 1980s, have a much greater resolution, generating voxels in the range of 5–50 μm, or approximately 1,000,000 times smaller than that produced by CT (236).

CT was the first radiological modality in which digital images could be produced instead of the directly provided analogue images. It creates grey-scale images of a series of sequential slices rather than superimposed images of complete object sections (243). It has been used in different fields of dentistry: implant treatment planning, temporo-mandibular joint examination and assessment of large cysts and tumours (244).

The main advantage of CT is that any external and internal features such as voids or cracks can be visualised with the samples remaining intact (21, 235, 245). An added
benefit is that the results are reproducible and can be accurately correlated to histological sections (246, 247). It has been used in various applications in endodontic research: in understanding root canal anatomy (248), evaluation of root canal morphology after instrumentation (249), assessing quality of obturation materials and techniques (41, 176), investigating the effect of ultrasonic removal of separated instruments on root canal walls (250), and assessing the effectiveness of various filling removal techniques in root canal retreatment (21).

### 3.1.2 Nikon Metris custom bay micro-CT

A Nikon micro-CT (225kV 3 µm source) (X-tek Systems Ltd., Tring, England) was used in this study. It is housed in a large customised walk-in bay (Figure 3.1). The size of this area and a heavy duty sample manipulator allow large specimens (up to 1m length and 100 kg weight) to be scanned. Magnified images can be recorded on the 2000 pixel (200 micron pixel pitch) detector allowing observation of fine differences in contrast. The X-ray attenuation is adjusted by changing the target material and accelerating voltage. A range of materials can be used as the target material for the X-ray source, such as copper, molybdenum, silver and tungsten. The interchangeable sources enables the use of the machine at energies ranging from ~40-230kV, which permits scanning of a wide variety of samples from biological specimens to high density metals (242).
Figure 3.1 Nikon micro-CT housed in a customised bay used to scan the samples. Controls (encircled) are used to orientate the sample (242).

Scan times range from 20 to 120 minutes. Resolution varies with the sample size. For samples up to 1 cm, the resolution is approximately 5 microns and for the largest samples (~20 cm), it is around 100 microns. Samples larger than 20 cm can be imaged by linking scans which can then be reconstituted during the reconstruction stage (242).

The sample is attached to a stage which is rotated through 360° in front of the X-ray source (Figure 3.2). This stage also allows the connection of a range of special rigs designed for in-situ 4D analysis (compression, tension and temperature). Two workstations are connected to the custom bay: one for data collection and the other for adjusting the X-ray parameters and the resulting image. The micro-CT settings used
are presented in Table 3.1. Voltage, current and time are optimised to get the best resolution. Contrast range can be adjusted to be the same for all samples.

Figure 3.2 A sample (root) is attached to a stage which is rotated in front of an X-ray source
Table 3.1 Micro-CT settings used to scan the samples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>93 kV</td>
</tr>
<tr>
<td>Current</td>
<td>135 micro Amps</td>
</tr>
<tr>
<td>Projections</td>
<td>1901 radiographs</td>
</tr>
<tr>
<td>Exposure time</td>
<td>1000 seconds</td>
</tr>
<tr>
<td>Gain</td>
<td>16</td>
</tr>
<tr>
<td>Sample-source distance</td>
<td>2 cm</td>
</tr>
<tr>
<td>Detector-sample distance</td>
<td>138 cm</td>
</tr>
</tbody>
</table>

3.1.3 Reconstruction of images

The acquired projections (Figure 3.3) were in the form of 2D 32 bit files which were reconstructed using CTPro 3D software (Version XT 2.2, Metris, Hertfordshire, UK) (Figure 3.4). The software allowed examination of the image set to look for aberrant X-rays, corrupt images, slippage of the object or any other scanning errors which may affect the reconstruction. If such defects were found, the samples were rescanned. Other set up corrections such as, beam hardening and noise reduction, were also established. The output volume was then defined by determining the region of interest to be reconstructed. The files produced after the reconstruction were:

- Recon.xml: contains the parameters of the reconstruction.
- Recon.vgi: contains description of volume graphics (used to import the CT volume file into the volume viewing software VGStudio MAX).
- Recon.vol: contains the data of volume graphics (the 3D reconstructed volume). It is usually a large file.
- Recon.log: log of activity for this reconstruction.

- Recon.xtekct: saved parameter file with the settings used to generate the volume.

VGStudio MAX 2.1 (Volume Graphics GMBH, Heidelberg, Germany) software was then used to convert the data to 16 bit files. This made them more convenient to visualise and analyse due to the reduced size of the files.

![2-dimensional image of a scanned sample before reconstruction](image)

**Figure 3.3** 2-dimensional image of a scanned sample before reconstruction
**Figure 3.4** Reconstruction of the acquired projections using CT Pro 3D software

### 3.1.4 Visualisation and analysis of images

A computer programme Avizo 6.3 Standard version (Visualization Sciences Group, Berlin, Germany) was used to visualize and analyze the data (Figure 3.5). 2D horizontal slices of the samples were viewed (Figure 3.6). This software has the advantage of permitting analysis of the images on grey scale and not just black and white (251). This makes it easy to view and differentiate between materials with different radiopacities. Different thresholding strategies were tested and one strategy was used to segment all samples. Different tools (Figure 3.5) like the brush, magic wand and threshold tool were used during segmentation (251). Using a line profile of the grey values, threshold values were determined to be: <30000 signify voids, >30000 signify filling material. However, when this was applied using the threshold tool, there were some voids which were not selected. We then tested two strategies: upper limits and lower limits for selecting those voids using the brush tool. The
resulting volumes, using the two strategies, were then plotted. The scatter per sample was found to be about 0.1%. The brush tool was then used at a range which is intermediate between the upper and lower limits. The volume of each material (including voids) was then calculated using a function in the software (measure materials statistics) which provides the volume of each material. Virtual 3D images of the root and filling were created using the same software (Figure 3.7).

Figure 3.5 Visualisation and segmentation of the reconstructed data using Avizo 6.3 Standard software. Tools used for segmentation are brush (blue circle), magic wand (yellow circle) and threshold tool (red circle).
Figure 3.6 2-dimensional slice of the reconstructed images
Figure 3.7 A virtual 3D image created using Avizo Standard software
3.2 Assessment of push-out bond strength using a universal testing machine

3.2.1 Introduction

The push-out bond test was initially used to evaluate bonding between bone and orthopaedic implants (252). Its first application in dental research was to investigate bonding of restorative materials to dentine (253). The material under investigation was packed into a cylindrical cavity prepared in slices of coronal dentine and then subjected to a push-out test (253). Since then, the test has been widely used in endodontic research to evaluate the bond strength of posts and filling materials to tooth tissue and to other materials (254). It is considered to be the best method of measurement of adhesion currently available (254).

The push-out test allows precise standardisation of the specimens with application of forces perpendicular to the dentinal tubules thus simulating the clinical situation (255). The bond strength is calculated from the force required to extrude the material from the root canal space and the interfacial surface area between the dentine wall and the material (256).

Although it has been shown that the push-out test is not suitable for thermoplastic materials such as gutta percha, which can deform under testing (25), the test has been used to measure the bond strength of different sealers (119, 257) with similar results found when the canal was entirely filled with the sealer alone (258, 259). Therefore, as the failure occurs at the interface rather than within the core material, the deformation of the core material does not negate the value of the test in comparing different filling materials (254).
3.2.2 Preparation of samples for the push-out test

The method of sample preparation and testing was adopted from previous studies (119, 120, 260). After completion of root canal treatment, the teeth were decoronated to the level of the cemento-enamel junction using a low-speed diamond wheel saw under continuous water coolant (Model 650, South Bay Technology inc., California, USA). A surveyor (Autenal Medizintechnik GmbH, Essen, Germany) (Figure 3.8) was used to help in aligning the roots vertically. The roots were then embedded in acrylic resin. After complete setting of the acrylic resin, the roots were sliced, using the diamond wheel saw, perpendicular to the long axis. The thickness of each slice was 2 mm, unlike that in the studies by Gesi et al. (119) and Skidmore et al. (120) who used 1 mm thick slices. This thickness was chosen because it has been reported that the formula of push-out bond strength works well for slices that are greater than 1.1 mm in thickness (261). The roots were sliced to the level of the apical third, where the canal size is very small and not appropriate to be used for the test. The canal shape was examined under a microscope to choose slices with a circular canal shape. Two slices per root were selected. The surface area of the bonding interface was calculated using the following formula (260):

\[ A = \pi (R + r) \sqrt{h^2 + (R - r)^2} \]

where \( \pi \) is the constant 3.14, \( R \) is the coronal radius of the canal, \( r \) is the apical radius of the canal, and \( h \) is the slice thickness, all measured in millimetres (mm). The formula used in the studies by Gesi et al. (119) and Skidmore et al. (120) is for the surface area of a cylinder. As the root canal is tapered, the formula used in this study is for a truncated cone.
Figure 3.8 A surveyor used to help in vertical alignment of the roots before embedding in acrylic resin

3.2.3 Push-out test using the Zwick universal testing machine

Each slice was mounted into the universal testing machine (Figure 3.9) with the coronal aspect facing the support jig so that the forces are applied in apico-coronal direction to avoid any interference from the canal taper. Two cylindrical plungers were used (0.78 and 0.50 mm in diameters) to apply force to the filling material without touching the canal walls. The root slices were placed on a support jig with a hole to allow extrusion of the filling material. The force was applied at a speed of 0.5 mm/minute until debonding occurred which was manifested by a sudden drop in the force as displayed by the force/displacement curve (Figure 3.10).
The bond strength (megapascals \([\text{MPa}]\)) was calculated using a modified formula (261):

\[
\left( \frac{F}{A} \right) \sqrt{\frac{E_d}{E_f}}
\]

where \( F \) is the force (Newtons), \( A \) is the interfacial surface area (mm\(^2\)), \( E_d \) is the elastic modulus of dentine (16000 MPa) (117), and \( E_f \) is the elastic modulus of the filling (Resilon) (86.58 MPa) (25).

**Figure 3.9** A root slice mounted in a universal testing machine to apply the push-out test
3.2.4 Scanning electron microscope examination of the debonded surface

A Philips XL30 field emission gun scanning electron microscope (FEGSEM), with a resolution of 3 nm, was used to examine the root canal wall after bond failure. This device has a range of detectors. A backscattered detector (BSD) is used to produce topographical, alignment and atomic number contrast. There is also an energy dispersive spectroscopy (EDS) analytical system which can identify elements from boron to uranium. Information about the granular and sub-granular orientation, boundary distribution and texture can be obtained by the electron backscattered diffraction system (EBDS). The two systems (EDS and EBDS) can be linked to help in phase identification (242).
Representative samples were selected. The slices were sectioned in a perpendicular direction to the root surface to allow visualization of the root canal wall. The canal wall was coated with gold/palladium at approximately 5 nm thickness using a PECS (precision etching and coating system).

3.3 Evaluation of root fracture resistance using a universal testing machine

3.3.1 Introduction

Root fracture is one of the most frustrating complications of endodontic treatment and usually results in extraction of the tooth (262). It is disappointing to both the patient and the dentist as it often occurs after all endodontic and prosthodontic treatment have been completed (263). Vertical root fracture represents about 2 to 5% of crown/root fractures with the highest incidence occurring in root canal treated teeth in patients who are more than 40 years old (264).

Vertical root fracture is usually characterized by a complete or incomplete fracture line which extends along the root surface to the apex (263). The most susceptible teeth are the maxillary premolars and the mesial roots of the mandibular molars (265). The narrow mesio-distal dimension compared with the bucco-lingual in these teeth makes it more susceptible to fracture especially after removal of additional tooth structure during root canal and post preparation (263).

The etiology of vertical root fracture is usually iatrogenic with the two main factors being root canal treatment procedures (e.g. excessive canal enlargement, excessive pressure during compaction of filling material) and the use of intra-radicular posts.
Diagnosis of vertical root fracture can be challenging. However, there are some differentiating parameters, such as a narrow, deep, isolated pocket associated with the affected tooth and a sharp pain on biting of hard food (265). When a post crown dislodges more than one time, a vertical root fracture should be suspected (265).

3.3.2 Preparation of the samples for mechanical testing

The experimental design and the method of sample preparation for the mechanical test used in the present experiment have been used in previous studies (104, 266, 267). After performing the root canal treatment, the roots were immersed in molten wax. Acrylic resin was mixed to a thin consistency and poured into a mould in which the roots were embedded. After complete setting of the resin, the blocks were quickly submerged in hot water and the resulting socket and the root surface were cleaned from any remnants of wax. A low-viscosity silicone was injected into the acrylic socket and the roots were repositioned into the socket resulting in a thin layer of silicone (0.22-0.32 mm) surrounding the root to resemble the periodontal ligaments (268).

3.3.3 Zwick universal testing machine

The resin blocks containing the embedded root were mounted into a jig (Figure 3.11) and a round tip (2.5 mm in diameter) was selected to apply the force directly on the root canal orifice. The Zwick universal testing machine (Figure 3.12) was set to apply compressive force (Newton) at a speed of 1 mm/minute until fracture occurred. The maximum force at fracture was recorded when there was a sudden and sharp
drop in the force as displayed on the stress/displacement curve (Figure 3.13). There was an audible sound in most cases.

Figure 3.11 A root embedded in acrylic resin is mounted into a jig in a universal testing machine
Figure 3.12 Zwick/Roell Z020 universal testing machine
Figure 3.13 Load/displacement curve displayed by the universal testing machine showing a gradual increase in the force (N) with a sharp drop indicating fracture.
3.4 Evaluation of leakage resistance using a dye leakage method

3.4.1 Introduction

Leakage through the root canal system has been investigated using a wide range of methods, including dye leakage, fluid filtration, glucose leakage, radioactive isotopes, electrochemical, and bacterial leakage. Dye leakage is considered the most widely used method for leakage assessment (183). Different types of dyes have been used, for example methylene blue (87), India ink (269), rhodamine B fluorescent dye (270) and basic fuchsine (271).

The use of a vacuum to prevent interference with dye penetration due to entrapped air has been suggested (189). However, it has been reported that the application of a vacuum has an insignificant effect on the extent of dye penetration (185).

Visualization of the extent of dye penetration into the root canal has been performed either by clearing or sectioning the root. The clearing method involves rendering the root transparent by decalcification and dehydration (272). In the sectioning technique, the root is sectioned either longitudinally (57) or horizontally (58) to examine the presence of dye under a microscope.

3.4.2 Dye leakage method

The teeth were decoronated. After performing root canal retreatment, the root surface was covered with two layers of nail varnish. Each root was submerged in 2% methylene blue dye in a plastic container where the root was kept upright to facilitate the passage of dye in coronal-apical direction.
There were three immersion periods: 1 day, 7 days and 30 days. After each period, 10 roots from every group were removed from the dye and washed under running water. The roots were then embedded in acrylic resin so that they could be easily clamped while being sectioned by a diamond wheel saw under water coolant at 2, 4, 6 and 8 mm from the coronal surface (Figure 3.14). After sectioning, the root canal was examined under a stereomicroscope microscope (x25) (MEIJI Techno Co. Ltd., Tokyo, Japan) (Figure 3.15) to detect the presence of dye (Figure 3.16).

Figure 3.14 A root embedded in a resin block is being sectioned horizontally using a diamond wheel saw
Figure 3.15 A stereomicroscope used to examine the samples to detect the extent of dye penetration
Figure 3.16 Slices from a representative sample examined under a microscope (x25) to detect dye penetration through the filled root canal. The dye is visible at 2 mm (A), 4 mm (B) and 6 mm (C), but not at 8 mm (D) section.
Chapter 4
Micro-CT evaluation of voids in the filling material of single-rooted teeth obturated with different techniques

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(Appendix: Published Paper 1)
4.1 Abstract

**Aim:** The aim of this study was to compare the volume of voids in a resin-based root canal filling (Resilon) with gutta percha using either cold lateral condensation or continuous wave of compaction filling techniques using computed X-ray microtomography (micro-CT).

**Methodology:** A total of 56 extracted upper anterior human teeth were decoronated, the canals shaped using rotary ProTaper files to a final size of F3 and randomly allocated into 4 groups (n=14) according to the filling material and obturation technique; Group 1: gutta percha/cold lateral (GP/C), Group 2: Resilon/cold lateral (R/C), Group 3: gutta percha/thermal (GP/T), Group 4: Resilon/thermal (R/T). Thermal filling was performed using System B and Obtura II. The filled roots were then scanned using micro-CT and the data were subsequently processed using Avizo 6.3 Standard version software. Statistical analysis was performed using the Kruskal-Wallis test with multiple pairwise comparisons.

**Results:** The total percentage volume of voids in GP/C (2.40%) and R/C (1.88%) were significantly higher than GP/T (1.04%) and R/T (1.29%) ($P<0.001$). A significantly higher percentage of voids was present in the coronal third compared with middle and apical thirds ($P<0.001$).

**Conclusion:** Thermal obturation resulted in a root filling with significantly fewer voids than the cold lateral condensation technique regardless of the obturation material used. Most of the voids located in the coronal third which emphasizes the importance of obtaining a good coronal seal following endodontic treatment.

**Key words:** computed tomography (CT); Resilon; voids
4.2 Introduction

Optimal obturation leads to successful endodontic treatment (273). Incomplete filling of a well-cleaned and prepared root canal system could compromise the outcome of treatment (273). The ideal obturation material should provide good adaptation to the canal walls and fill any irregularities with the full length of the canal being densely filled with a homogenous mass of obturation material (7).

Gutta percha (GP) has been the material of choice for obturation for many years as it possesses favourable properties such as dimensional stability, good working properties, ease of removal, biocompatibility and radiopacity (23). One of the limitations of GP is that it does not bond to any type of sealer (28). As many sealers shrink upon setting, there is a potential for gaps or voids creation via which microleakage may occur (48, 56).

A resin-based material, Resilon, was introduced in 2004 (19). It has been claimed that it bonds to the root canal dentine, strengthens the root when used as an obturation material, (18, 104, 120, 274) and provides a better seal than GP (48, 56). It has similar handling properties as GP and can be placed into root canals using either cold lateral condensation (41, 64) or thermal obturation (42, 46).

Many properties of Resilon have been investigated such as leakage resistance (48), root strengthening (18, 104) and quality of obturation (41). However, most of these studies relate to it when used with cold lateral condensation and very few have compared it with thermal obturation (42). As the use of heated filling techniques is increasing (238), investigation of the quality of obturation with Resilon using this method in comparison with cold lateral condensation is timely.

The few studies which have investigated Resilon using thermal obturation in comparison with cold lateral condensation have used a variety of assessment methods which may result in inaccuracies. In one study (42), the filled roots were sectioned and examined under a stereomicroscope. This process may lead to loss of some of the filling material and creation of spaces that may appear as voids. In the
present study, micro-CT was used as it gives highly accurate three-dimensional analysis of voids (246).

The aim of this study was to compare the percentage volume of voids in root canals filled with Resilon and with GP using cold lateral condensation and continuous wave of compaction techniques. The null hypothesis was that there would be no significant difference in the percentage volume of voids between the four combinations of the two materials and obturation techniques.
4.3 Materials and Methods

This study was approved by the ethics committee at the University of Manchester (Reference number: UREC5-10275). Seventy upper anterior human teeth were collected, disinfected with 5% sodium hypochlorite (NaOCl) (Procter and Gamble, Weybridge Surrey, UK) for 10 minutes and stored in normal saline. Exclusion criteria were: roots that were carious, fractured, resorbed or immature. Roots with sclerosed canals, with more than one canal or those with root curvature >10°, as determined by Schneider (275), were also excluded.

Preparation

From the initial sample, a total of 56 teeth (28 lateral incisors, 16 central incisors and 12 canines) were selected according to the aforementioned criteria. The teeth were decoronated and the length of the roots was reduced to 14 mm using a diamond wheel saw with water cooling (central incisors, lateral incisors and canines were kept separate to facilitate in their allocation into groups for obturation). The working length was determined to be 1 mm short of the apical foramen using a size 10 K-file (VDW GmbH, Munich, Germany).

The root canals were prepared using rotary ProTaper files to the final size of F3 (Dentsply Maillefer, Ballaigues, Switzerland) and irrigated with 1% NaOCl. After completion of the preparation, the root canals were irrigated with 5 mL 17% ethylene-diamine-tetra-acetic acid (EDTA) (PPH Cerkamed, Sandomierska, Poland) and 10 mL distilled water.

Obturation of root canals

The roots were randomly allocated into four groups using a stratified sampling method (n=14: 7 lateral incisors, 4 central incisors and 3 canines) according to the filling material and obturation technique.

Group 1 (GP/C) was filled with ProTaper GP F3 (Dentsply Maillefer, Ballaigues, Switzerland) and AH Plus sealer (Dentsply DeTrey GmbH, Konstanz, Germany) using cold lateral condensation. A master cone was selected and trimmed to fit the
canal to the working length with tug-back. Then, the canal was dried using paper points (Diadent, Chungcheongbuk-do, Korea). The sealer was carried into the canal using the master cone. A finger spreader (Dentsply Maillefer, Ballaigues, Switzerland) was used to compact the GP cone and create a space for accessory points. When obturation was completed, the GP points were cut to the coronal end of the root using a heated instrument and the coronal part was compacted using a Machtou plugger (Dentsply Maillefer, Ballaigues, Switzerland).

Group 2 (R/C) was filled with Resilon/RealSeal (Pentron Corp., Wallingford, US) sealer using cold lateral condensation according to the manufacturers’ instructions. A Resilon point (30/0.06) was used as the master cone which was trimmed to fit the canal to the working length with tug-back. After drying the root canal with paper points, RealSeal primer was applied. RealSeal sealer was carried to the canal on the master cone. Cold lateral condensation was performed as previously described. The coronal surface was light cured for 40 seconds.

Group 3 (GP/T) was filled with ProTaper GP/AH Plus sealer using a continuous wave of compaction technique. The sealer was carried to the canal using the master cone. A System B plugger of fine-medium size (SybronEndo, Glendora, USA) was selected and a rubber stopper was fitted 5 mm short of the working length, marking the binding point. The heat source was adjusted to 200°C. The plugger was activated and used to cut the excess GP and then inserted into the canal along the master cone until the binding point was reached. The heat source was then deactivated and a firm pressure was maintained for 10 seconds. A one-second heat burst was activated and the plugger was withdrawn. The canal was then backfilled with GP pellets (Obtura Spartan, Earth City, Missouri, US) using Obtura III at 200°C (Obtura Spartan, Earth City, Missouri, US).

Group 4 (R/T) was obturated with Resilon/RealSeal sealer using the continuous wave of compaction technique described above. The temperature setting in system B and Obtura III was set to 150°C according to the manufacturers’ instructions.

All roots were stored for 72 hours at 37°C and 100% humidity in air-tight containers.
Scanning of the roots

The roots were scanned in a random order using a 225kV 3 µm source Nikon micro-CT housed in a walk-in enclosure (Nikon X-tek Systems Ltd., Tring, England). Using a sample-source distance of 2 cm and a detector-sample distance of 138 cm, magnified images were collected on a 2000 pixel (200 micron pixel pitch) detector allowing observation of fine differences in contrast. The X-ray attenuation could be adjusted by changing the target material and accelerating voltage. For this scan, copper was used as the target material. The micro-CT settings were: 93 kV, 135 micro Amps, 1901 projections (radiographs), 1000 seconds exposure, gain 16.

The raw data were reconstructed using CTPro 3D software (Version XT 2.2, Metris, Hertfordshire, UK). An effective voxel size of 7.7-9.3 µm was obtained. Voids were observed in 2-dimensional (2D) (Figure 4.1) and 3-dimensional (3D) images (Figure 4.2) using Avizo 6.3 Standard version (Visualization Sciences Group, Berlin, Germany). A number of grey-scale thresholding values were tried and the upper and lower limit values demonstrated that the scatter per sample was found to be about 0.1% volume of voids. After segmentation, Avizo software was used to measure the total volume of voids. The percentage volume of voids was calculated using the following equation:

\[
\frac{\text{Total volume of voids}}{\text{Total volume of the canal}} \times 100
\]

Statistical analysis

Test of normality showed that data were not normally distributed and therefore, non-parametric tests were used. Analysis of data was carried out using the Kruskal-Wallis test with multiple pairwise comparisons. The software used was SPSS Version 20.0 (IBM Corp., Armonk, US) with the level of significance set at 5%.
Figure 4.1 Visualisation of reconstructed images showing virtual 2D slices of filling (A) gutta percha/cold lateral condensation, (B) Resilon/cold lateral condensation, (C) gutta percha/thermal compaction, (D) Resilon/thermal compaction. The arrows indicate voids within the filling material and the scale bars are 5 mm long.
Figure 4.2 3D images of the root canal fillings in (A) gutta percha/cold lateral condensation, (B) Resilon/cold lateral condensation, (C) gutta percha/thermal compaction, (D) Resilon/thermal compaction. The blue colour within the filling material indicates voids; the scale bars are 6-8 mm long.
4.4 Results

The means and standard deviations (SD) of the overall percentage (%) of voids are shown in Table 4.1. The GP/C (gutta percha/cold lateral) group showed the highest overall mean value (2.40%), whereas the GP/T (gutta percha/thermal) group had the lowest overall value (1.04%). The Kruskal-Wallis test indicated that there was a statistically significant difference between the groups ($P<0.001$). The multiple pairwise comparisons showed that Groups GP/C and R/C (Resilon/cold lateral) had significantly higher percentage of voids than Groups GP/T and R/T (Resilon/thermal) ($P<0.001$ for GP/C versus GP/T and $P=0.007$ for R/C versus R/T).

Table 4.2 shows the means and standard deviations of the percentage of voids in each third of the root canal. In the coronal and the middle thirds, the results were similar to those for the overall percentage of voids (GP/C and R/C showed significantly higher percentage of voids than GP/T and R/T) ($P<0.05$). In the apical third, there was no significant difference between the groups. When the thirds were compared for each group, the coronal third showed significantly higher percentage of voids than the middle third, which had significantly higher percentage of voids than the apical third ($P<0.001$). The percentage of voids in the coronal third in relation with the overall percentage of voids was 68.8% in GP/C, 75.5% in R/C, 70.2% in G/T and 73.7% in R/T.
### Table 4.1 Means and standard deviations of the overall percentage of voids

<table>
<thead>
<tr>
<th>Group</th>
<th>Overall voids % mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP/C</td>
<td>2.40&lt;sup&gt;a&lt;/sup&gt; (0.66)</td>
</tr>
<tr>
<td>R/C</td>
<td>1.88&lt;sup&gt;a&lt;/sup&gt; (0.61)</td>
</tr>
<tr>
<td>GP/T</td>
<td>1.04&lt;sup&gt;b&lt;/sup&gt; (0.44)</td>
</tr>
<tr>
<td>R/T</td>
<td>1.29&lt;sup&gt;b&lt;/sup&gt; (0.44)</td>
</tr>
</tbody>
</table>

GP/C: gutta percha/cold lateral condensation  
R/C: Resilon/cold lateral condensation  
GP/T: gutta percha/thermal compaction  
R/T: Resilon/thermal compaction  
Different superscript letters indicate statistically significant differences.

### Table 4.2 Means and standard deviations of the percentage of voids in each third of the root canal

<table>
<thead>
<tr>
<th>Group</th>
<th>Coronal voids % mean (SD)</th>
<th>Middle voids % mean (SD)</th>
<th>Apical voids % mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP/C</td>
<td>1.65 (0.60)</td>
<td>0.66 (0.22)</td>
<td>0.09 (0.05)</td>
</tr>
<tr>
<td>R/C</td>
<td>1.42 (0.57)</td>
<td>0.44 (0.21)</td>
<td>0.02 (0.01)</td>
</tr>
<tr>
<td>GP/T</td>
<td>0.73 (0.30)</td>
<td>0.27 (0.20)</td>
<td>0.04 (0.03)</td>
</tr>
<tr>
<td>R/T</td>
<td>0.95 (0.40)</td>
<td>0.26 (0.12)</td>
<td>0.08 (0.06)</td>
</tr>
</tbody>
</table>

GP/C: gutta percha/cold lateral condensation  
R/C: Resilon/cold lateral condensation  
GP/T: gutta percha/thermal compaction  
R/T: Resilon/thermal compaction  
The differences between the thirds in all groups are statistically significant. GP/C and R/C have significantly higher volume of voids than GP/T and R/T in the coronal and middle thirds.
4.5 Discussion

Traditional methods used to evaluate the quality of root fillings allow only partial evaluation of the root canal content. Radiographs give a two-dimensional view of a three-dimensional structure. Sectioning the roots to view them using a scanning electron microscope or a stereomicroscope could result in loss of some of the material which may mimic voids. Further, the chance of intersecting a void is statistical and the shape of the voids may mean that volume fractions are not properly inferred from 2D sections. The clearing technique is time consuming (177) and the long periods of immersion in alcohol may affect the physical properties of gutta percha (276). Recently, the use of computed tomography (CT) (176, 177, 235) and micro-CT (277-279) in dental research has gained increasing popularity. It gives an accurate three-dimensional view of the root canal content without destroying the samples which can be used for further research (41). In the present study, the voxel size obtained was 7.7-9.3 µm, which is better than that used in previously published studies (12, 41).

The null hypothesis was rejected as the results showed a statistically significant difference in the volume of voids between the tested groups. The cold lateral condensation technique with both materials showed a significantly higher percentage of voids in comparison with the thermal technique. This agrees with previous studies (176-178) which compared the two techniques using gutta percha. In cold lateral condensation, the resulting mass is not homogenous and there may be spaces present between the points. By contrast, the thermal technique produces a more homogenous mass with fewer voids and better adaptation of the filling to the canal walls (177, 178). However, during condensation with pluggers, air could be entrapped. None of our samples were void-free. This finding has also been reported in previous studies (39, 40, 42).

Our study showed that the GP/C group had a higher percentage of voids than the R/C group, but this was not statistically significant. This is consistent with other studies (39, 40, 43), but is in contrast with that found by Hammad et al. (41). In the latter study (41), the lowest percentage of voids was found in the GP group as compared
with Resilon, GuttaFlow and EndoRez. The sealer used with GP was Tubliseal (a zinc-oxide eugenol-based sealer), whereas in the present study AH Plus sealer (a resin-based sealer) was used. It has been reported that GP showed volumetric expansion when it came into contact with eugenol which resulted in a better seal of the obturation (280). In addition, the voxel size used in the present study was lower than that used in the study by Hammad et al. (41) which improved detection of smaller voids. This may explain the fewer voids in the GP group reported by Hammad et al. (41).

In contrast with the findings of Hammad et al. (41), the results of the present study showed that the coronal third in all groups contained a significantly higher percentage of voids than the middle and apical thirds. This may have a clinical significance if the coronal seal lost as it may accelerate penetration of fluids through the root canal filling and dissolution of the sealer. In both obturation techniques used in this study, the apical third of the canal was filled with a master cone. In the cold lateral condensation technique, the remainder of the canal was filled with accessory points which were packed using a spreader leading to a greater risk of void creation between the accessory points in the middle and coronal thirds as opposed to the apical third. Similarly, in the thermal obturation technique, the middle and coronal thirds were obturated with a softened filling material in which air bubbles may be entrapped during condensation. This may explain the significant difference in the percentage of voids between the thirds.

Voids inside the filling materials, which are not linked to the periphery of the filling, could be considered less clinically significant than peripheral gaps because microorganisms, if present, are restrained in an unfavourable environment and do not have access to a nutritional supply. Peripheral gaps along the dentine-sealer or core material-sealer interfaces may jeopardize the outcome of root canal treatment (273). This is because they may act as a pathway that permits sealer dissolution and passage of micro-organisms through the filled root canal to the periradicular tissues. Furthermore, if residual micro-organisms remain trapped in the dentinal tubules after treatment is finished, the peripheral gaps may form channels through which the micro-organisms can get access to nutrients and initiate or continue the inflammatory process.
This is an *in vitro* study and further *in vivo* investigations are indicated. Variations in the canal anatomy of the human teeth may affect the obturation quality. Ideally, contralateral teeth from the same individual should be used (281). However, this is not practical in research settings and limits the sample size. Therefore, upper anterior teeth were used in this study and each group contained equal number of central incisors, lateral incisors and canines (stratified sampling). It would be beneficial in the future to extend the testing to a wider range of root curvatures as this would be more clinically relevant.

### 4.6 Conclusion

The results of the present study show that the percentage of voids in the fillings is low (1.04-2.40%), regardless of the filling technique. However, the significant difference shown highlights the importance of the use of continuous wave of compaction technique in reducing the volume of voids in the root canal filling. In addition, the significantly higher percentage of voids in the coronal third in comparison with the middle and the apical thirds emphasizes the significance of obtaining a good coronal seal after completion of endodontic treatment.

### 4.7 Acknowledgement

The authors deny any conflicts of interest. We are grateful to the EPSRC whose grant funding (EP/I02249X, EP/F007906 and EP/F028431) enabled the purchase and support of the imaging equipment in the Henry Moseley X-ray Imaging Facility.
Chapter 5

Effect of calcium hydroxide and its combination with iodoform on the bond strength of Resilon

(Submitted to the Journal of Adhesive Dentistry)
5.1 Abstract

The aim of this study was to investigate the effect of calcium hydroxide (CH) and its aqueous- or oil-based combinations with iodoform on Resilon bond strength. Fifty extracted human upper anterior teeth were selected. Root canal treatment was performed using ProTaper rotary files. The teeth were allocated into five groups (n=10): Group 1 (control), no medicament; Group 2, CH; Group 3, aqueous CH and iodoform (Calcipast1); Group 4, oil-based CH and iodoform (Vitapex); Group 5, iodoform. After one week storage, the medicaments were removed and the canals were obturated with Resilon. The teeth were embedded in acrylic resin and sectioned into 2 mm slices. The slices were mounted in a Universal Testing Machine and loaded until bond failure occurred. The mean bond strength of the control (18.68 MPa), CH (15.36 MPa) and Calcipast1 (16.82 MPa) groups were significantly higher than that of the Vitapex (5.13 MPa) and iodoform (5.46 MPa) groups ($P \leq 0.001$). Vitapex and iodoform decreased the bond strength of Resilon. It may be recommended to avoid the use of these medicaments if Resilon is the obturation material.

**Key words:** bond strength, calcium hydroxide, iodoform, Resilon, Vitapex
5.2 Introduction

The main goal of chemo-mechanical preparation is to disinfect the entire root canal system (282). The complexity of the root canal system and limited access of the disinfection methods to intra-canal spaces restrict the total removal of micro-organisms (283). The main function of intra-canal medicaments during endodontic treatment is to disinfect the root canal (284, 285). The most commonly used medicament is calcium hydroxide (CH) due to its biocompatibility and activity against a wide range of micro-organisms (286). However, there are conflicting reports regarding its effectiveness against Enterococcus faecalis, a commonly isolated bacterium from failed endodontically-treated roots. Some studies have reported significant antibacterial activity against \textit{E faecalis} (287-290), while others have reported that it is not effective (291-294).

CH can be mixed with different vehicles. Some of these are oil-based, such as Vitapex (Neo Dental Chemical Products Co. Ltd., Tokyo, Japan), which contains 40.4% iodoform, 30.3% calcium hydroxide and 22.4% silicone oil (295). Others are aqueous, such as Calcipast1 (PPH Cerkamed, Sandomierska, Poland), which promote rapid ion release and are easier to remove than oil-based vehicles (286).

Adhesive filling materials, such as Resilon (Pentron Corp., Wallingford, USA), have been introduced in endodontic treatment in an attempt to improve the coronal and apical seal (48). Resilon contains a matrix (co-polymer of polycaprolactone and urethane dimethacrylate), bioactive glass and radiopaque fillers (28). It can bond to the root dentine and form a “monoblock” (28). This bond to dentine can be weakened by materials used during endodontic treatment such as sodium hypochlorite (157), chlorhexidine (239) and some intra-canal medicaments (240).

The total removal of intra-canal medicaments from the root canal may not be possible (296). The remnants may interfere with the bond of adhesive filling materials by acting as a physical barrier. In addition, the high pH of CH can neutralise the acidic primer in self-etching adhesive systems (30). The effect of CH on the bond strength of Epiphany sealer has been investigated (297, 298) and also compared to the effect of chlorhexidine (240). The literature does not contain any
reports on the effect of other medicaments used in endodontic treatment on the bond strength of Resilon.

Therefore, the aim of this study was to investigate the effect of intra-canal medicaments (CH, Calcipast1, Vitapex, and iodoform) on the bond strength of Resilon to dentine. The null hypothesis was that there would be no significant difference in the bond strength of Resilon to dentine after the use of these medicaments.
5.3 Materials and Methods

This study was approved by the Ethics Committee of the University of Manchester (UREC5-10275). Upper anterior human teeth were collected, disinfected for 10 minutes with 5% sodium hypochlorite (NaOCl) and stored in normal saline. The roots were inspected under illumination and magnification to exclude those with cracks, caries or resorption. Fifty teeth (10 central incisors, 30 lateral incisors and 10 canines) were included in the study.

Teeth preparation

Access cavities were prepared and the canals were cleaned and shaped using rotary ProTaper files (Dentsply Maillefer, Ballaigues, Switzerland) to a final size of F4. 5 mL 1% NaOCl (Procter and Gamble, Weybridge Surrey, UK) was used for irrigation. After completion of the canal preparation, the canals were irrigated with 5 mL 17% ethylene-diamine-tetra-acetic acid (EDTA) (PPH Cerkamed, Sandomierska, Poland) and finally 10 mL distilled water. The canals were dried using paper points (Diadent, Chungcheongbuk-do, Korea) and the teeth were then randomly assigned into five groups using stratified sampling (n=10, 2 central incisors, 6 lateral incisors and 2 canines) according to the type of intra-canal medicament:

Group 1 (control): no medicament.

Group 2 (CH): Calcipast (PPH Cerkamed, Sandomierska, Poland).

Group 3 (CH1): Calcipast1, aqueous combination of CH and iodoform (PPH Cerkamed, Sandomierska, Poland).

Group 4 (VP): Vitapex, silicone oil-based combination of CH and iodoform (Neo Dental Chemical Products Co. Ltd., Tokyo, Japan).

Group 5 (IO): Iodoform (PPH Cerkamed, Sandomierska, Poland).

CH, CH1 and Vitapex were placed into the canals using plastic tips. Iodoform was applied into the canals using a lentulo spiral filler (Dentsply Maillefer, Ballaigues,
Switzerland) until the canals were totally filled with the medicament to the level of the canal orifice. After the canal was filled with the medicament, the access cavity was sealed with a temporary filling (Coltosol, Coltène, Altstätten, Switzerland) and the teeth were stored for one week in a moist environment at 37°C.

**Obturation of the root canals**

The intra-canal medicaments were removed from the canals using a size 25 hand K-file and agitated irrigation with 5 mL 1% NaOCl using a 10 mL syringe and a 27 gauge needle. The removal of iodoform and Vitapex was assisted by the use of ethanol (Whatman International Ltd, Maidstone, UK) according to the manufacturer's recommendations. The removal of the medicaments was considered complete when the canal walls appeared clean under magnification (X2.0) (Orascoptic, Middleton, USA) and no material could be seen on the file. Paper points were also used to detect any remaining medicament. The root canals were then irrigated with 5 mL 17% EDTA and 10 mL distilled water.

The root canals were obturated with Resilon/RealSeal sealer (Pentron Corp., Wallingford, US) using System B (SybronEndo, Glendora, USA) and Obtura III (Obtura Spartan, Earth City, Missouri, USA). A master cone which fitted to the working length with tug-back was selected. After drying the canals with paper points, RealSeal primer was applied. The master cone was covered with the sealer and inserted into the canal. The heat source was set to 150°C. The system B plugger (fine-medium size) was inserted into the canal along the master cone to 5 mm short of the working length. The heat application was then stopped and apical pressure was maintained for about 10 seconds. A one-second heat burst was activated and the plugger was withdrawn. Backfilling of the canal was performed using Obtura III at 150°C. The coronal surface was light cured for 40 seconds.

The access cavity was closed with temporary filling and the teeth were stored for one week in a moist environment at 37°C.
Preparation for the push-out test

The teeth were decoronated to the level of the cemento-enamel junction using a low-speed diamond wheel saw under continuous water coolant (Model 650, South Bay Technology inc., California, USA). The roots were embedded in acrylic resin (Metrodent Ltd, Huddersfield, UK) and then horizontally sectioned into 2 mm thick slices. Only slices with circular canal shape were included (2 slices per root, n=20 slices per group). The thickness of each slice was measured with a digital caliper (Mitutoyo Corp. Kawasaki, Japan), and all were within 1.9–2.2 mm. The interfacial area of the root filling was calculated using the formula (260):

\[ A = \pi (R + r) \sqrt{h^2 + (R - r)^2} \]

where \( \pi \) is the constant 3.14, \( R \) is the coronal radius of the canal, \( r \) is the apical radius of the canal, and \( h \) is the slice thickness, all measured in millimetres (mm).

The slices were marked to ensure that the load was applied in apical-coronal direction to avoid any interference owing to root canal taper. Two flat ended cylindrical plungers with diameters of 0.78 and 0.50 mm were used to apply the force on the filling material. Each slice was positioned carefully so that the plunger contacted only the filling material (Figure 5.1). A support jig with a hole was selected to provide enough clearance for the filling material when it was extruded from the slice. Compressive loading was performed using a Universal Testing Machine (Zwick GmbH & Co. KG, Germany). Loading was applied at a speed of 0.5 mm/minute until a sharp and instant drop of the applied force was observed on the load/displacement curve which indicated bond failure. Failure was also manifested by extrusion of the filling material from the root slice (Figure 5.2).

The bond strength (megapascals [MPa]) was computed using a modified formula (261):

\[ \left( \frac{F}{A} \right) \sqrt{\frac{E_d}{E_f}} \]
where $F$ is the force (Newton), $A$ is the interfacial surface area (mm$^2$), $E_d$ is the elastic modulus of dentine (16000 MPa) (117), and $E_f$ is the elastic modulus of the filling (Resilon) (86.58 MPa) (25).

**Figure 5.1** Schematic representation for the set-up for push-out bond strength test (A). Image for a root slice in the universal testing machine (B).

**Figure 5.2** Image of a root slice before performing the push-out test (A). The filling material (Resilon) was extruded from the root canal after performing the test (B: apical aspect, C: coronal aspect).
Analysis of Failure Modes

Both sides of each slice were examined under a stereomicroscope microscope (MEIJI Techno Co. Ltd., Tokyo, Japan) at x25 magnification to determine the mode of bond failure. Three failure modes were identified: (1) adhesive failure at the filling material/dentine interface, (2) cohesive failure within the filling material, and (3) mixed failure in both the filling material and dentine interface.

Scanning electron microscope (SEM) evaluation

A representative sample from each group was randomly selected for SEM examination. Each sample was sectioned perpendicular to the root surface to allow visualisation of the root canal wall after bond failure. The samples were coated with gold/palladium at approximately 5 nm thickness using a PECS (precision etching and coating system). They were then scanned using the Philips XL30 FEG SEM (field emission gun scanning electron microscope) (FEI, Tokyo, Japan).

Statistical Analysis

SPSS Version 20.0 (IBM Corp., Armonk, US) was used to analyse the data. A normality test showed that the data were not normally distributed and therefore, non-parametric tests were used. The significance level was set at ≤0.05. Data were analysed using the Kruskal-Wallis test with multiple pairwise comparisons.
5.4 Results

The means and standard deviations of the bond strength (MPa) of Resilon for all groups are presented in Table 5.1 and Figure 5.3. The control group showed the highest bond strength (18.68 MPa) and VP group showed the lowest bond strength (5.13 MPa). The Kruskal Wallis test showed that there was a significant difference between the groups ($P \leq 0.001$). The control, CH and CH1 groups had significantly higher bond strengths than VP and IO groups ($P \leq 0.001$). There was no significant difference between the first three groups (control, CH, CH1) and neither between the last two groups (VP, IO).

As shown in Table 5.2, the mode of bond failure was predominately adhesive in the groups VP (60%) and IO (55%). In the control and CH1 groups, the main failure mode was mixed (55% and 45%, respectively), whereas in CH group, it was cohesive (50%). SEM examination of the root canal wall after bond failure showed the three failure modes (Figure 5.4).

<table>
<thead>
<tr>
<th>Group (n=20)</th>
<th>Mean bond strength (MPa)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>18.68$^a$</td>
<td>3.92</td>
</tr>
<tr>
<td>Calcipast</td>
<td>15.36$^a$</td>
<td>5.85</td>
</tr>
<tr>
<td>Calcipast 1</td>
<td>16.82$^a$</td>
<td>3.74</td>
</tr>
<tr>
<td>Vitapex</td>
<td>5.13$^b$</td>
<td>1.78</td>
</tr>
<tr>
<td>Iodoform</td>
<td>5.46$^b$</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Different superscript letters indicate statistical significant difference
Figure 5.3 A bar chart for the means of the bond strength of the groups. The error bars represent standard deviations.

Table 5.2 Modes of bond failure

<table>
<thead>
<tr>
<th>Group</th>
<th>Adhesive n (%)</th>
<th>Cohesive n (%)</th>
<th>Mixed n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>3 (15)</td>
<td>6 (30)</td>
<td>11 (55)</td>
</tr>
<tr>
<td>Calcipast</td>
<td>2 (10)</td>
<td>10 (50)</td>
<td>8 (40)</td>
</tr>
<tr>
<td>Calcipast 1</td>
<td>4 (20)</td>
<td>7 (35)</td>
<td>9 (45)</td>
</tr>
<tr>
<td>Vitapex</td>
<td>12 (60)</td>
<td>1 (5)</td>
<td>7 (35)</td>
</tr>
<tr>
<td>Iodoform</td>
<td>11 (55)</td>
<td>2 (10)</td>
<td>7 (35)</td>
</tr>
</tbody>
</table>
Figure 5.4 SEM images illustrate the types of Resilon-to-dentine bond failure. (A) Adhesive failure shows canal surface clean of filling material. (B) Cohesive failure shows surface covered with sealer. Filler particles of the sealer can be observed (arrows). (C) Mixed failure shows areas clean and others covered with sealer. (D) A higher magnification (x1000) of a section from (A) (square) shows some open dentinal tubules (open arrows) and others occluded with fractured resin tags (solid arrows).
5.5 Discussion

The results of the present study showed that the use of the intra-canal medicaments, Vitapex and iodoform, resulted in significantly lower bond strengths of Resilon to dentine in comparison with CH and CH1. Therefore, the null hypothesis was rejected. The effect of CH on the bond strength of Resilon has been previously investigated (240, 297, 298). There has been no previous investigation of the bond strength of Resilon when CH has been combined with iodoform using different vehicles.

The significantly reduced bond strength of Resilon after the use of Vitapex and iodoform may be attributed to their composition. Both Vitapex and iodoform contain silicone oil (295) which may make removal of these medicaments difficult (299) and may therefore interfere with the bonding of Resilon resulting in lower bond strengths. This may also explain the mode of failure in these groups which was predominately at the root filling-dentine interface (adhesive failure).

Our study showed that CH had no significant effect on the bond strength of Resilon. This was in agreement with a previous study (298) and disagreed with some others (240, 297). Barbizam et al. (240) reported that CH significantly reduced the bond strength of Epiphany sealer to dentine. In their study, the coronal and middle thirds of the root canals were prepared using a cylindrical post drill after preparing the canals with RACE Ni Ti files. The resulting shape of the canal may interfere with proper removal of the intra-canal medicaments. In addition, the canal was filled with the sealer without using Resilon core. This may explain the different results.

Slices with canals that are not circular in shape were excluded to avoid non-uniform stress distributions during testing and inaccurate measurements (120, 261). The slices which were used in the test were mainly from the middle third of the root. In the coronal third, the canal shape was oval, and in the apical third, the canal size was very small. Removal of the iodoform and Vitapex was assisted by alcohol as per the manufacturer’s recommendation. However, as a final rinse with alcohol results in dry canal and the dentine surface needs to be moist for effective bonding (300), the canals were irrigated with distilled water as a final rinse.
Bond strength tests are the best measure of adhesion currently available (254). However, the push out bond strength test has some limitations with regard to the diameter of pins used, modulus of elasticity of the filling material tested and the specimen thickness (261). In the present study, efforts were made to minimise these limitations. The diameters of the pins used in the test were chosen so that they were just slightly smaller than the canal diameter and the ratio between the pin diameter and the canal diameter was less than 0.85. Therefore, the stress was concentrated near the dentine-filling interface (254, 261). In calculating of the bond strength, we used the correction factor \( \sqrt{\frac{E_d}{E_f}} \) suggested by Chen et al. (261) because the modulus of elasticity of Resilon (86.58 MPa) (25) is lower than that of the dentine (16000 MPa) (117). The thickness of the root slices was standardised at 2 mm as it has been reported that the formula of push-out bond strength works well for slices that are greater than 1.1 mm in thickness (261). The formula to calculate the interfacial surface area used in some previous studies (120, 127) was for a curved surface of a cylinder and in others (301) was not stated. However, the root canal walls are tapered and therefore we used the formula for a curved surface of a truncated cone (260). Bond strength is only one aspect of the quality of root canal seal. Further investigation of the effect of the medicaments on other properties of Resilon is required.

In conclusion, our study showed that Vitapex and iodoform significantly decreased the bond strength of Resilon in comparison with CH and CH1. Within the limitations of this in vitro study, it is recommended to avoid the use of Vitapex and iodoform if the canal is to be obturated with Resilon.
Chapter 6

Micro-CT evaluation of the effectiveness of the combined use of rotary and hand instrumentation in removal of Resilon

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(Appendix: Published Paper 2)
6.1 Abstract

This study compares the effectiveness of ProTaper rotary files with ProTaper retreatment and K-files in the removal of Resilon or gutta percha (GP) from canals filled either by cold lateral condensation or thermal obturation using micro-CT. Ninety-six teeth were prepared using ProTaper files and allocated into four groups (n=24): Group-1 was filled with GP/AH Plus and Group-2 with Resilon/RealSeal using cold lateral condensation. Group-3 was filled with GP/AH Plus and Group-4 with Resilon/RealSeal using System B and Obtura II. The roots were scanned by micro-CT. Each group was divided into two subgroups (n=12): A, retreated using ProTaper files and B, using ProTaper retreatment and K-files. The roots were scanned to calculate the volume of the remaining material. With thermal obturation, roots filled with Resilon had significantly more remaining material than GP. Obturation using thermal technique resulted in significantly less remaining material than cold condensation except Resilon retreated using ProTaper retreatment and K-files.

Key words: Computed tomography (CT), Gutta percha, ProTaper, Retreatment, Resilon
6.2 Introduction

Periradicular diseases may persist or emerge following the completion of root canal treatment as a result of intra-radicular infection, extra-radicular infection or non-microbial factors (191). The main cause of failure is persistent, or recurrent microbial infection (192, 193). Non-surgical retreatment is usually the preferred option for teeth in which endodontic treatment has failed as there is a greater opportunity to eradicate any intra-radicular source of infection compared with a surgical approach (202). Retreatment comprises removal of the old root filling material to allow access to any residual micro-organisms and permit further cleaning and disinfection of the root canal system (202). Additionally, efficient removal of previous filling materials can facilitate intimate contact between the sealer and the root canal walls, thus potentially preventing microleakage (204).

Gutta percha is the most commonly used root canal filling due to its favourable properties such as dimensional stability, biocompatibility and ease of removal (23). However, it does not bond to sealer (28). A resin-based root canal filling, Resilon, was launched in 2004 (19). It is capable of bonding to methacrylate-based sealers and as such may result in the prevention of microleakage and strengthening of the root treated tooth (18, 92).

Root filling materials can be removed by a variety of techniques such as the use of stainless steel or nickel-titanium hand files, nickel-titanium rotary files or ultrasonic instruments with or without the adjunctive use of solvents or heat (207, 209). Studies have compared the effectiveness of either rotary to hand instrumentation (21, 205) or compared different rotary systems (207, 216). The combined use of hand instruments
and rotary files for effective removal of filling materials has been advocated (21), but no study has investigated the effectiveness of a combination of the two.

Several studies have investigated the ease of removal of Resilon compared with gutta percha (21, 207, 209). So far, however, there has been no published data related to the relationship between removal success and method of filling technique (i.e. cold lateral condensation versus thermal obturation).

The aim of this study, therefore, was to investigate the effectiveness of rotary instrumentation and its combination with hand instrumentation in the removal of gutta percha and Resilon placed into root canals by either cold lateral condensation or continuous wave of compaction technique using micro-CT. The null hypothesis was that there would be no significant difference in the removability between the tested materials, techniques of obturation and techniques of removal.
6.3 Materials and methods

Ethical approval for this study was obtained from the Ethics Committee at the University of Manchester. Upper anterior human teeth were collected, placed in 5% sodium hypochlorite (NaOCl) for 10 minutes and then stored in normal saline. Examination of the roots was performed under magnification (x40) to exclude roots with cracks, fracture, resorption, caries or immature apices or those with a root curvature of more than 10°, as described by Schneider (275).

Preparation of teeth

Ninety-six upper anterior teeth (48 central incisors, 24 lateral incisors and 24 canines) were selected according to the criteria noted above. Teeth were decoronated and root lengths were reduced to 14 mm using a diamond wheel saw with water cooling (Model 650, South Bay Technology inc., California, USA). Central incisors, lateral incisors and canines were kept separate to facilitate in their allocation into groups for obturation. The working length was determined to be 1 mm short of the apical foramen using a size 10 K-file (VDW GmbH, Munich, Germany). A glide path was established and the canals were prepared using rotary ProTaper Universal files (Dentsply Maillefer, Ballaigues, Switzerland) to size F3. The motor used was an X-smart (Dentsply Maillefer, Ballaigues, Switzerland) with a contra angle hand-piece. The canals were irrigated with 1 mL 1% NaOCl (Procter and Gamble, Weybridge Surrey, UK) after each filing. When the preparations were completed, the root canals were irrigated with 5 mL 17% ethylene-diamine-tetra-acetic acid (EDTA) (PPH Cerkamed, Sandomierska, Poland) and 10 mL distilled water.
Obturation of root canals

The roots were randomly allocated into four groups using stratified sampling (n=24, 12 central incisors, 6 lateral incisors and 6 canines) based on the material and technique of obturation:

Group 1 (GP/C) was filled with ProTaper gutta percha (Dentsply Maillefer, Ballaigues, Switzerland) and AH Plus sealer (Dentsply DeTrey GmbH, Konstanz, Germany) using cold lateral condensation. A suitable master cone (fitted the canal to the working length with tug-back) was selected and the canal was dried using paper points. The sealer was applied using the master cone. A finger spreader (Dentsply Maillefer, Ballaigues, Switzerland) was used to compact the cone and accessory points were inserted into the resulting space until obturation was completed. The gutta percha points were cut to the coronal end of the root using a heated instrument and the coronal part was condensed using a Machtou plugger (Dentsply Maillefer, Ballaigues, Switzerland).

Group 2 (R/C) was filled with Resilon/RealSeal (Pentron Corp., Wallingford, USA) sealer using cold lateral condensation. A master cone of size 30/0.06 was selected. RealSeal primer was applied and the excess was removed using paper points. The sealer was applied using the master cone. Lateral condensation was completed as described for Group 1. The coronal surface was light cured for 40 seconds as recommended by the manufacturers.

Group 3 (GP/T) was filled with ProTaper gutta percha/AH Plus sealer using continuous wave of compaction technique. A System B plugger of fine-medium size (SybronEndo, Glendora, USA) was used and a rubber stopper was adjusted to 5 mm
short of the working length. The temperature was set to 200°C in the touch mode. The excess GP was cut using the hot plugger which was then inserted alongside the master cone until the rubber stopper reached a reference point. The heat application was then stopped and apical pressure was maintained for 10 seconds. The plugger was withdrawn after one-second activation of the heat source. Backfilling was performed using Obtura III at 200°C (Obtura Spartan, Earth City, Missouri, USA).

Group 4 (R/T) was obturated with Resilon/RealSeal sealer using System B and Obtura III as explained for Group 3. Temperature in System B and Obtura III was set to 150°C according to the manufacturers’ instructions. All roots were stored in airtight containers for a week at 37°C and 100% humidity. All the root fillings were carried out by one operator.

**Scanning of the roots**

Teeth were scanned in random order using a Nikon micro-CT (225kV 3 µm source) (X-tek Systems Ltd., Tring, England) housed in a customised bay. Images were collected on a 2000 pixel detector using a sample-source distance of 2 cm and a sample-detector distance of 138 cm which allowed observation of fine differences in contrast. The target material could be changed which allowed adjustment of the X-ray attenuation by accelerating voltage. Copper was chosen as the target material. The micro-CT settings were: 93 kV, 135 micro Amps, 1901 projections (radiographs), 1000 seconds exposure, gain 16.
Retreatment

Each group was divided into two subgroups (n=12, 6 central incisors, 3 lateral incisors and 3 canines). In both subgroups, the coronal 2 mm of the filling was removed using Gates Glidden drills (3 and 4) (Dentsply Maillefer, Ballaigues, Switzerland). Then, two drops of eucalyptus oil (PPH Cerkamed, Sandomierska, Poland) were placed in the space made available. In subgroup A, the filling material was removed using rotary ProTaper Universal files (F1, F2 and F3) (at 300 rpm) and in subgroup B using rotary ProTaper Universal retreatment files (D1, D2 and D3) (Dentsply Maillefer, Ballaigues, Switzerland) (at 500 rpm as per the manufacturer’s recommendation) followed by hand K-files (25 and 30). ProTaper Universal and retreatment files were used at the following penetration depths: F1 and D1 to the coronal third, F2 and D2 to the middle third and F3 and D3 to the apical third. In subgroup B, hand K-files (25 and 30) were used to the full working length in a circumferential quarter-turn push-pull motion. The criteria for completion of the treatment were clean canal walls and no material on the files as observed by the naked eye. When retreatment completed, irrigation was performed using 3 mL 1% NaOCl, 5 mL 17% EDTA and finally, 10 mL distilled water. Root canals were dried using paper points. All the retreatment work was carried out by one operator.

Scanning of the roots

The Nikon micro-CT was used to scan the roots for the second time using the same settings as for the first scan. The raw data from the first and second scan were reconstructed using CTPro 3D software (Version XT 2.2, Metris, Hertfordshire,
UK). A voxel size of 7.7-9.3 µm was obtained. Using Avizo 6.3 Standard version (Visualization Sciences Group, Berlin, Germany), the total filling and the remaining material were viewed in three-dimensional images. The total volume of filling was measured from the data of the first scan and the total volume of the remaining material from the second scan. The percentage of the volume of the remaining material was then calculated.

Statistical analysis

SPSS Version 20.0 (IBM Corp., Armonk, US) was used with the level of significance set at \( p \leq 0.05 \). Data were found to be not normally distributed and therefore, nonparametric tests were used. Analysis of data was carried out using Kruskal-Wallis test with multiple pairwise comparisons.
6.4 Results

Table 6.1 shows means and standard deviations of the overall percentage volume of remaining material. Resilon/cold lateral group (R/C) retreated using ProTaper Universal rotary files showed the highest percentage volume of remaining material (3.94%) and gutta percha/thermal group (GP/T) retreated using ProTaper Universal rotary files showed the lowest percentage (1.34%). When the thermal obturation technique was used, teeth filled with Resilon were found to have significantly more remaining material than gutta percha when they were removed using ProTaper Universal retreatment files and hand K-files ($P=0.028$) and using ProTaper Universal files ($P=0.013$). There was no significant difference between Resilon and gutta percha when the cold lateral condensation technique was used.

**Table 6.1** Means and standard deviations (SD) of the overall percentage volume of remaining material in the tested groups

<table>
<thead>
<tr>
<th>Filling material</th>
<th>Obturation technique</th>
<th>Gutta percha Mean % (SD)</th>
<th>Resilon Mean % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P</td>
<td>PH</td>
</tr>
<tr>
<td>Cold lateral condensation</td>
<td></td>
<td>2.80 (0.37)</td>
<td>2.85 (0.62)</td>
</tr>
<tr>
<td>Continuous wave of compaction</td>
<td></td>
<td>1.34 (0.33)</td>
<td>1.45 (0.40)</td>
</tr>
</tbody>
</table>

P: ProTaper Universal files, PH: ProTaper retreatment files and hand K-files. The two obturation techniques are significantly different except with Resilon when removed by PH. Resilon is significantly different from gutta percha when continuous wave of compaction technique used irrespective to the removal technique.
On comparison of the techniques of obturation, the continuous wave of compaction resulted in significantly less remaining material than the cold lateral condensation technique in all groups except the Resilon group retreated using ProTaper Universal retreatment files and hand K-files ($P=0.004$ for the gutta percha group retreated using ProTaper Universal files and $P=0.018$ for the Resilon group retreated using ProTaper Universal files). There was no significant difference between the retreatment techniques used. As shown in Table 6.2, the remaining material in the apical third was found to be significantly more than in the middle and the coronal thirds in all groups. Figure 6.1 illustrates reconstructed three-dimensional images for a representative sample filled with gutta percha before and after retreatment.

**Table 6.2** Means and standard deviations (SD) of the percentage volume of remaining material in each third of the root canal in the tested groups

<table>
<thead>
<tr>
<th>Obturation technique</th>
<th>Retreatment technique</th>
<th>Gutta percha Mean % (SD)</th>
<th>Resilon Mean % (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P</td>
<td>PH</td>
</tr>
<tr>
<td>Cold lateral condensation</td>
<td>Coronal</td>
<td>0.24 (0.12)</td>
<td>0.12 (0.08)</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>0.63 (0.32)</td>
<td>0.50 (0.26)</td>
</tr>
<tr>
<td></td>
<td>Apical</td>
<td>1.93 (0.60)</td>
<td>2.23 (0.67)</td>
</tr>
<tr>
<td>Continuous wave of compaction</td>
<td>Coronal</td>
<td>0.05 (0.03)</td>
<td>0.03 (0.02)</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>0.18 (0.08)</td>
<td>0.32 (0.25)</td>
</tr>
<tr>
<td></td>
<td>Apical</td>
<td>1.11 (0.31)</td>
<td>1.10 (0.27)</td>
</tr>
</tbody>
</table>

P: ProTaper Universal files, PH: ProTaper retreatment files and hand K-files. The apical third is significantly different from the other two thirds in all groups.
Figure 6.1 Reconstructed three-dimensional images show roots (a) filled with gutta percha (b) before retreatment (A) and the remaining gutta percha after removal (B).
6.5 Discussion

The present study showed that when Resilon was removed significantly more material remained than in teeth filled with gutta percha when a continuous wave of compaction technique was used. It was also found that obturation using the cold lateral condensation technique resulted in significantly more remaining material than the continuous wave of compaction technique after removal in all groups except the Resilon group retreated using ProTaper Universal retreatment files and hand K-files. Removability of Resilon in comparison with gutta percha has been previously investigated using different retreatment techniques \((21, 209, 228)\). However, no study has compared the outcome of removal of the two root filling materials when placed into the canal using different techniques. In addition, the effectiveness of the combined use of hand and rotary instrumentation has not been examined before. Very few studies have used micro-CT to measure the volume of the remaining material \((21)\). In this study, micro-CT was used as it gives an accurate three-dimensional image of the remaining material.

Resilon matrix is composed of co-polymers of polycaprolactone and urethane dimethacrylate. The dimethacrylate component enables Resilon to be bonded to various dual-cure methacrylate-based resin sealers which in turn bond to the root canal dentine forming a “monoblock” \((20, 136)\). By contrast, gutta percha, which is composed of zinc oxide and gutta percha \((17)\), does not bond to any type of sealers \((28)\). This may explain the significantly greater volume of Resilon remaining compared with gutta percha found when the thermal obturation technique was used. Similar results have been reported in previous studies \((209, 227)\), but contradictory results have also been found \((21, 207)\). It has been reported that complete setting of
RealSeal sealer takes about 30 minutes in an anaerobic environment, but may take one week in an aerobic field (231). In the study by Hammad et al. (21), the time allowed for the sealer to set was 72 hours, whereas in this study, the roots were stored for a week. Therefore, the low volume of Resilon reported in the former study (21) may be attributed to the incomplete setting of the sealer.

But why was the difference between Resilon and gutta percha significant only with the thermal obturation technique and not with the cold lateral obturation technique? It has been reported that softened Resilon flows better than gutta percha into lateral canals (46). Therefore, there would be more residual Resilon than gutta percha in the lateral canals after removal. In addition, it has been found that eucalyptus oil is more effective on thermoplastic gutta percha than conventional gutta percha (22) and this may explain the results obtained in this study.

It was found that obturation using cold lateral condensation resulted in significantly more residual material than the continuous wave of compaction after removal in all groups except the Resilon group retreated using ProTaper Universal retreatment files and hand K-files. The latter technique may require a smaller quantity of sealer and form a more homogenous mass than the former (177, 209). Hence, there would be a lesser amount of sealer to be eliminated and easier removal of the homogenous mass. When ProTaper Universal retreatment files and hand K-files were used, the difference between the two obturation techniques with Resilon was not significant. This may be attributed to the equal effectiveness of this technique in removal of Resilon with both obturation techniques. Previous studies which compared the effectiveness of hand with rotary instrumentation reported contrasting results (21, 219, 224). This may be due to differences in the rotary systems tested, type of hand
file and time allowed for setting of sealers. The current study found no significant
difference in the effectiveness of removal between ProTaper Universal rotary files
and the combined use of ProTaper Universal retreatment files and hand K-files. The
retreatment in the ProTaper Universal groups was performed up to a file size F3,
whose tip size is 30, and to size 30 hand K-file in the combined ProTaper Universal
retreatment files and hand K-files groups. The standardisation of the size of the
apical enlargement may explain the insignificant difference found.

The results of this study showed that the remaining material in the apical third was
significantly more than the middle and coronal thirds in all tested groups. This was
in agreement with previous studies which investigated different retreatment
techniques (209, 215). During retreatment, the material in the coronal and middle
thirds is more accessible via both mechanical and chemical removal techniques than
the material in the apical third. In addition, the material may be pushed to the apical
third during removal. Furthermore, the root canal anatomy in the apical third is
complicated with lateral canals and ramifications which make complete removal of
the filling material very difficult (302).

Micro-CT was used in this study as it has been shown that it gives a highly accurate,
non-destructive, three-dimensional view of the internal structure of the root (12, 41).
Other methods of assessment used in earlier studies such as radiographs, splitting or
clearing of roots may not be accurate as they only yield partial evaluation of the
remaining material (205, 207, 219).

Variations in the anatomy of the human teeth such as lateral canals and other root
canal ramifications may influence the removal of the filling material. However, the
roots were randomly allocated into groups and therefore they were equally affected. As this is an *in vitro* study, caution should be exercised when these results are extrapolated to a clinical situation. The percentages of the remaining material shown in this study, although significantly different, are actually small (1.34–3.94%) and clinical studies are needed to see if these differences are clinically significant.

6.6 Conclusion

The current findings show that retreatment of teeth filled with Resilon resulted in more residual material than those filled with gutta percha when a thermal compaction technique was used. This may highlight the need for meticulous care if this resin-based root filling material needs to be removed. Removal of Resilon and gutta percha from teeth filled using cold lateral condensation resulted in more residual material than those filled using thermal compaction. The combined use of rotary and hand instrumentation may not be superior to rotary instrumentation alone if the size of apical enlargement in retreatment, in relation with the primary treatment, is considered.
6.7 Acknowledgement

The authors deny any conflicts of interest. We are grateful to the EPSRC whose grant funding (EP/I02249X, EP/F007906 and EP/F028431) enabled the purchase and support of the imaging equipment in the Henry Moseley X-ray Imaging Facility.

We also thank Dr. Tanya Walsh for her helpful advice on the statistical analysis.
Chapter 7
Fracture resistance of Resilon-filled roots following different retreatment techniques

(Accepted for publication in the Journal of Research and Practice in Dentistry)
7.1 Abstract

**Aim:** The aim of this study was to investigate whether endodontically retreated teeth filled with Resilon are more resistant to fracture than those filled with gutta percha following hand or rotary removal techniques.

**Methodology:** Seventy-two upper anterior human teeth were selected, decoronated and reduced to 12 mm. The canals were shaped using rotary ProTaper files and randomly assigned into two groups (n=36). Obturation was performed using gutta percha/AH Plus in Group 1 and Resilon/RealSeal in Group 2. The roots were stored for one week at 37°C. The roots were then randomly allocated into three subgroups: A (n=10), no further treatment was performed. In B (n=13), the filling was removed using hand K-files and in C (n=13) using ProTaper retreatment files. Subgroups B and C were refilled using the same materials as used in the primary treatment and stored for one week. Three roots from each of the four subgroups were left unfilled to act as a control (n=12). All roots were embedded in resin and subjected to fracture in a universal testing machine. Data were analysed using Kruskal-Wallis with multiple pairwise comparisons.

**Results:** Resilon-refilled roots showed no significance difference in fracture resistance compared with gutta percha-refilled roots regardless of the retreatment technique. There was no significant difference in fracture resistance between the two retreatment techniques.

**Conclusion:** When used as a root filling material, Resilon was found not to increase the fracture resistance of primarily and previously root filled teeth regardless of the retreatment technique.

**Key words:** Gutta percha; ProTaper; Resilon; retreatment; root fracture
7.2 Introduction

Root fracture is one of the causes of endodontic treatment failure and usually results in tooth extraction (263). Endodontic treatment inherently requires the removal of tooth structure in order that a straight line access is created and to permit thorough cleaning and shaping (99). The strength of the treated tooth is directly proportional to the quantity and quality of remaining tooth structure. The more tooth structure is removed, the likelihood of tooth fracture increases (100).

Theoretically, if the root canal filling material bonds to the root dentine, in addition to providing a good seal, fracture resistance of the root may be improved (28). Gutta percha has favourable properties, such as dimensional stability, biocompatibility and removability which make it the most commonly used obturation material (23). However, its main limitation is that it does not bond to the root dentine or to any sealer (28). Therefore, it does not provide any resistance to fracture of the root canal treated teeth (25, 104).

A thermoplastic synthetic polymer-based root filling material, Resilon, was introduced in 2004 (19). It is comprised of a matrix (co-polymer of polycaprolactone and urethane dimethacrylate), bioactive glass and radiopaque fillers (bismuth oxychloride and barium sulphate) (28). It is produced in points, as is gutta percha, and can be used to obturate the canal using either cold lateral condensation or warm filling techniques. If indicated, it can be removed using heat or solvents as with gutta percha (21). The literature indicates that Resilon has some promising properties compared with gutta percha in that it bonds to the dentine (28), provides more favourable resistance to leakage (48) and improves resistance to fracture (18).
The effect of Resilon in increasing fracture resistance of root canal treated teeth has been investigated in primary root canal treatment (104, 274), but its significance in retreatment cases has not been addressed nor have the effects of different techniques for its removal as a filling material. In cases of retreatment, roots may become even more susceptible to fracture as a result of further removal of dentine. Furthermore, any remaining material may interfere with the bonding of Resilon to the dentine wall (30).

Therefore, the aim of this study was to investigate the fracture resistance of previously root treated roots refilled with Resilon in comparison with gutta percha following retreatment using either hand K-files or ProTaper retreatment files. The null hypothesis is that there would be no significant difference in fracture resistance between roots refilled with Resilon compared with gutta percha using the two different retreatment techniques.
7.3 Materials and methods

The use of extracted human teeth in this study was approved by the Ethics Committee at the University of Manchester. Eighty-five upper anterior teeth were disinfected in 5% sodium hypochlorite (NaOCl) (Procter and Gamble, Weybridge Surrey, UK) for 10 minutes and stored in normal saline. Teeth were carefully examined under illumination and magnification (x40) to exclude any roots with cracks or fractures, resorption, immature apices, caries or roots with curvature more than 5°, as described by Schneider (275) The experimental design and the method of samples preparation for the mechanical test used in the present experiment have been used in previous studies (104, 267, 303).

Teeth preparation and obturation

The crowns were removed and the length of the roots was reduced to 12 mm using a diamond wheel saw with water cooling (Model 650, South Bay Technology inc., California, USA). Teeth were identified (central incisors, lateral incisors and canines) to aid in their allocation into groups for obturation. Bucco-lingual (BL) and mesio-distal (MD) dimensions of the roots were measured and roots with comparable dimensions were selected (Table 7.1). From the initial sample, 72 roots (28 central incisors, 22 lateral incisors and 22 canines) were suitable for the study.
Table 7.1 Means and standard deviations (SD) of bucco-lingual and mesio-distal dimensions (mm) of the roots of all subgroups

<table>
<thead>
<tr>
<th>Group</th>
<th>Control</th>
<th>Gutta percha</th>
<th>Resilon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>*A   **B     ***C</td>
<td>A     B     C</td>
</tr>
<tr>
<td>Mean BL dimension (SD)</td>
<td>6.81 (0.36)</td>
<td>6.67 (0.33)</td>
<td>6.91 (0.48)</td>
</tr>
<tr>
<td>Mean MD dimension (SD)</td>
<td>4.86 (0.39)</td>
<td>4.59 (0.41)</td>
<td>4.69 (0.43)</td>
</tr>
</tbody>
</table>

*A: No retreatment
**B: Retreated with hand K-files and refilled with the same material in the first treatment
***C: Retreated with ProTaper retreatment files and refilled with the same material in the first treatment

A size 10 K-file (VDW GmbH, Munich, Germany) was used to determine the working length, which was set at 1 mm short of the apical foramen. Root canals were prepared using rotary ProTaper files (Dentsply Maillefer, Ballaigues, Switzerland) to a final size of F3. 1% NaOCl was used as an irrigant. When preparation was finished, the canals were irrigated with 17% ethylene-diamine-tetra-acetic acid (EDTA) (PPH Cerkamed, Sandomierska, Poland) and distilled water. The roots were randomly allocated into two groups using stratified sampling (n=36: 14 central incisors, 11 lateral incisors and 11 canines) according to the filling material: Group 1 was filled with ProTaper gutta percha (GP) (Dentsply Maillefer, Ballaigues, Switzerland) and AH Plus sealer (Dentsply DeTrey GmbH, Konstanz, Germany) and Group 2 was filled with Resilon/ReaSeal sealer (Pentron Corp., Wallingford, US).

The root canals were dried using paper points (Diadent, Chungcheongbuk-do, Korea). In Group 1, a ProTaper GP master cone was selected (fitted the canal to the working length with tug-back), coated with the sealer and inserted into the canal. The cone was compacted using a System B plugger of fine-medium size (SybronEndo, Glendora, USA) with the temperature set at 200°C. Light vertical
pressure was applied for 10 seconds and then the plugger was withdrawn by applying a one-second heat burst. The canal was backfilled using Obtura III (Obtura Spartan, Earth City, Missouri, USA) at 200°C.

Group 2 was filled with Resilon/ReaSeal sealer using the thermal technique as described for Group 1. The primer was applied into the canal after drying and the excess was removed using a paper point. The sealer was carried on a Resilon master cone (30/0.06). As per the manufacturers’ instructions, the temperature was adjusted to 150°C for System B and Obtura III. After completion of obturation, the coronal part was light cured for 40 seconds. All roots were stored for one week at 37°C and 100% humidity in air-tight containers.

**Retreatment**

The roots in each group were randomly assigned into three subgroups (Figure 7.1):

A (n=10: 4 central incisors, 3 lateral incisors, 3 canines): no further treatment was performed.

B (n=13: 5 central incisors, 4 lateral incisors, 4 canines): the root filling material was removed using hand K-files.

C (n=13: 5 central incisors, 4 lateral incisors, 4 canines): the root filling material was removed using ProTaper retreatment files (Dentsply Maillefer, Ballaigues, Switzerland).
Figure 7.1 Groups and subgroups allocation according to filling materials and retreatment techniques
In subgroup B, the coronal 2 mm of the filling was removed using Gates-Glidden drills (Quality Endodontic Distributors Ltd, Peterborough, UK), then two drops of eucalyptus oil (PPH Cerkamed, Sandomierska, Poland) were placed in the canal. Hand K-files were then used in a circumferential quarter-turn push–pull filing motion until the filling material was removed such that no material was seen on the file or on the canal walls by naked eye. During removal, one or two drops of eucalyptus oil were applied as required. The final K-file size used was 30.

In subgroup C, ProTaper retreatment D1 file was used to remove the coronal one-third of the filling. The speed of the motor was set at 500 rpm according to the manufacturers’ recommendations. Eucalyptus oil was applied as in the subgroup B. D2 and D3 were then used to remove the filling from the middle and the apical thirds respectively.

After completion of removal, the canals were irrigated with 3 mL 1% NaOCl, 5 mL 17% EDTA and finally with 10 mL distilled water. The root canals were re-filled using the same materials and technique used in the first treatment of each subgroup. Three roots (1 central incisor, 1 lateral incisor, 1 canine) from each of the subgroups B and C were not refilled and assigned as a control group (n=12). Roots were stored at 37°C and 100% humidity for one week in air-tight containers.

**Mechanical testing**

All roots were dipped into molten wax and then embedded in acrylic resin (Metrodent Ltd, Huddersfield, UK). After the resin had set, it was immersed in hot water for 10 seconds to melt the wax and get the root out. The root surface and the resulting socket were cleaned from any remnants of wax and dried. Low-viscosity
vinyl polysiloxane material (3M ESPE, St. Paul MN, USA) was then poured into the acrylic resin socket and the root was repositioned into the socket resulting in a thin layer (0.22-0.32 mm) of silicone to simulate the periodontal ligaments (268) (Figure 7.2). The blocks of resin with the embedded roots were mounted into a Universal Testing Machine (Zwick GmbH & Co. KG, Germany). A tip with a round end (2.5 mm in diameter) was used to apply a vertical loading force directly above the root canal orifice. The force (Newton [N]) was applied at a speed of 1 mm/minute until the root fractured. Fracture was considered as the point at which a sharp and instant drop of the applied force was observed. The test was terminated when a 25% drop in the maximum force recorded.

Figure 7.2 A longitudinal section of a sample illustrating root (a) filled with gutta percha (b), surrounded by a thin layer of silicone (c) and embedded in acrylic resin (d)
Statistical analysis

SPSS Version 20.0 (IBM Corp., Armonk, US) was used at a level of significance of \( P \leq 0.05 \). Test of normality showed that data were not normally distributed and therefore, non-parametric tests were used. Data were analysed using the Kruskal-Wallis test with multiple pairwise comparisons.

7.4 Results

Means and standard deviations of the force required to fracture for all groups are presented in Table 7.2 and Figure 7.3. There was no significant difference between the four non-refilled control subgroups which showed similar results when compared with all test subgroups and therefore they were pooled into one representative control group. The results showed that the control group had significantly lower resistance to fracture than all filled groups regardless of the filling material or the retreatment technique. There was no significant difference in forces required to fracture between roots filled with Resilon and those filled with gutta percha irrespective of the retreatment technique \((P>0.05)\). There was also no significant difference in the forces between the two retreatment techniques regardless of the obturation material \((P>0.05)\). Mode of fracture was bucco-lingually in 74% of the samples and oblique in 26% (Figure 7.4).
Table 7.2 Means and standard deviations (SD) of force (Newton) required to fracture for all subgroups

<table>
<thead>
<tr>
<th>Group</th>
<th>Control (non-refilled)</th>
<th>Gutta percha</th>
<th>Resilon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*A</td>
<td>**B</td>
<td>***C</td>
</tr>
<tr>
<td>Mean SD (N)</td>
<td>169.36</td>
<td>261.06</td>
<td>281.44</td>
</tr>
<tr>
<td></td>
<td>10.01</td>
<td>63.78</td>
<td>67.12</td>
</tr>
</tbody>
</table>

*A: No retreatment

**B: Retreated with hand K-files and refilled with the same material in the first treatment

***C: Retreated with ProTaper retreatment files and refilled with the same material in the first treatment

Figure 7.3 A bar chart showing means and standard deviations of maximum force (Newton) at fracture for subgroups (A) no retreatment (B) retreated with hand K-files and refilled with the same material in the first treatment (C) retreated with ProTaper retreatment files and refilled with the same material in the first treatment.
Figure 7.4 Mode of fracture: (A) bucco-lingual, (B) oblique
7.5 Discussion

This study showed that Resilon, as a root filling material, did not increase the fracture resistance of retreated and non-retreated roots in comparison with gutta percha. Properties of Resilon in retreatment, such as sealing ability and bond strength (128, 304), have been investigated. However, fracture resistance of roots refilled with Resilon has not been examined. Furthermore, the effect of either hand or rotary removal techniques on fracture resistance has not been investigated.

It has been claimed that Resilon has a root strengthening effect which has been attributed to its ability to form a monoblock with the dentine wall whereby Resilon bonds to RealSeal sealer which in turn bonds to dentine (136). In the present study, Resilon did not improve the fracture resistance of primarily treated and retreated roots in comparison with gutta percha. This is in agreement with the findings of other reported work related to primary endodontic treatment (108-110, 305) and contradicts others (18, 103, 104). Some other studies reported that the fracture resistance of Resilon-filled roots were significantly lower than gutta percha-filled roots (106, 107). The contradiction may be due to differences in the samples preparation and study design. The roots in both studies (106, 107) were embedded in resin without the use of silicone tubing.

In order to prevent debonding of a resin material as a result of stress concentration at the interface with dentine, the material should have a modulus of elasticity similar to that of dentine (25). The modulus of elasticity of dentine is about 16,000 MPa (117), whereas that of Resilon is about 86.58 MPa (25) which is far below the dentine.
Therefore, the ability of Resilon to strengthen endodontically treated roots has been questioned (25, 306).

The use of silicone tubing around the root to simulate the cushioning effect of the periodontal tissues was used because it has been shown that unusually high forces to fracture might be necessary otherwise (303, 307, 308). The light-body condensation reaction silicone was used in the present study because it has a modulus of elasticity of 0.26 MPa (309) which is approximate to that of the human periodontal ligaments (0.11-0.96 MPa) (310). Full coverage of roots with silicone and acrylic resin was adopted to simulate clinical situation. 1% NaOCl was used as the irrigant in this experiment. It has been shown that high concentrations of NaOCl can significantly reduce the microhardness, flexural strength and modulus of elasticity of root canal dentine (311, 312). As all root canals were irrigated with the same concentration of NaOCl, all samples should be equally affected.

As this is an in vitro study, it does not take into consideration the in vivo tissue response. In addition, the natural variations in the anatomy of human teeth may influence the strength of the roots. However, the number of variables was decreased by standardising factors, such as root length and final size of canal preparation, and by equal allocation of upper anterior teeth in each group using stratified sampling and selecting comparable bucco-lingual and mesio-distal dimensions.

In conclusion, the current findings add to a growing body of literature which question the root strengthening effect of Resilon and indicate that it still could not be a replacement of gutta percha. Further in vivo investigation is warranted.
7.6 Acknowledgment

The authors would like to thank Dr. Tanya Walsh for her helpful advice on the statistical analysis of the data.
Chapter 8

Leakage resistance of Resilon-filled roots following different retreatment techniques
8.1 Abstract

**Aim:** This study investigated the effect of hand and rotary retreatment techniques on the leakage resistance of roots filled with Resilon.

**Methods:** A hundred human anterior teeth were decoronated leaving roots of 12 mm. The canals were shaped using ProTaper rotary files to size F3. Obturation was performed with Resilon using System B and Obtura III. 5 roots were obturated with a single Resilon cone without sealer to act as a positive control. After one week storage in a moist environment at 37°C, the roots were allocated into 3 groups (n=30): Group 1: no further treatment was performed, Group 2: retreated using hand K-files and Group 3: retreated using ProTaper retreatment files. Refilling in groups 2 and 3 was performed as in the first treatment. All surfaces, apart from the coronal of the roots were covered with two layers of nail varnish. Five roots, which were not retreated, were completely covered with nail varnish to act as a negative control. The roots were then immersed in 2% methylene blue dye and subdivided into three groups according to the period of immersion in the dye: one day, one week and one month. The roots were then cross-sectioned at 2, 4, 6 and 8 mm from the coronal surface. Each section was examined under a stereomicroscope microscope at x25 magnification for examination of dye leakage. A score was given to each sample according to the extent of dye leakage. Data were analysed using Kruskal Wallis test.

**Results:** There was no significant difference in the extent of dye leakage between the non-retreated group and the groups retreated using either hand K-files or ProTaper retreatment files. The leakage of dye increased significantly with time in all groups.
**Conclusion:** Leakage resistance of Resilon-refilled root canals was not significantly different from that through primarily treated root canals. The retreatment techniques investigated in this study had no effect on the leakage resistance of Resilon which deteriorated significantly over time.
8.2 Introduction

Following thorough chemo-mechanical cleaning, complete obturation and sealing of the root canal system is required for success (7). Failure of the treatment can occur due to persistent or secondary intra-radicular infection (191, 192). To eliminate residual apical infection following endodontic treatment, retreatment, endodontic surgery or an extraction are the options. The success rate at 4-6 years for retreatment procedures is 83%-92% (313, 314), that for endodontic surgery is 71.8% (314).

The aim of retreatment is total removal of the filling material in order that any micro-organisms persisting after the original treatment or having entered at a later stage via coronal defects and periodontal pockets are accessed and eliminated (203). Complete removal of the previous filling material is also essential to ensure intimate contact between the sealer and the root canal walls in the re-filled tooth thus preventing microleakage and avoid the risk of further failure (10).

Adhesive endodontic filling materials are potentially advantageous in that the root dentine to obturation material seal is optimised (28). One such material is Resilon which is composed of polycaprolactone, urethane dimethacrylate, bioactive glass and radio-opaque fillers (20). Its form and handling properties are similar to gutta percha. It is provided in ISO standardised cones and pellets for thermoplastic injection techniques. It can be removed for retreatment using heat or solvents (21).

The ability of Resilon to bond to dentine has been claimed to improve the seal of the root canal system (48). The leakage resistance of Resilon has been previously investigated in primary treatment (48, 49) and retreatment (315). In retreatment, filling materials are removed using a variety of techniques such as with stainless
steel or nickel-titanium hand files, nickel-titanium rotary files or ultrasonic
instruments with or without the adjunctive use of solvents or heat (207, 209).
Different techniques have been described to remove Resilon (21, 216), all of which
can result in residual material remaining adherent to the canal walls and thus
potentially resulting in leakage. There has been no previous investigation of the
effect of the retreatment technique on the leakage resistance of Resilon used as a
retreatment material.

The aim of this study therefore was to investigate the leakage resistance of Resilon
following retreatment using either hand K-files or ProTaper retreatment files. The
null hypothesis was that there would be no significant difference in the leakage
resistance between the two retreatment techniques at different time intervals.
8.3 Materials and methods

Ethical approval for the use of human teeth in this study was obtained from the Ethics Committee of the University of Manchester. Extracted upper anterior human teeth were collected, soaked in 5% sodium hypochlorite (NaOCl) for 10 minutes and then stored in normal saline. The roots were examined under magnification to detect any cracks, caries or resorption. A hundred teeth (31 central incisors, 49 lateral incisors and 20 canines) were included in the study.

**Preparation of teeth**

The teeth were decoronated and root lengths were reduced to 12 mm using a diamond wheel saw with continuous water cooling (Model 650, South Bay Technology inc., California, USA). The working length was determined to be 1 mm short of the apical foramen using a size 10 K-file (VDW GmbH, Munich, Germany). The canals were prepared using rotary ProTaper Universal files (Dentsply Maillefer, Ballaigues, Switzerland) to size F3. 5 mL 1% NaOCl (Procter and Gamble, Weybridge Surrey, UK) was used for irrigation using a 10 mL syringe and a 27 gauge notched needle (Kendall Monoject, Mansfield, Massachusetts, USA) after each filing. The root canals were finally irrigated with 5 mL 17% ethylene-diamine-tetra-acetic acid (EDTA) (PPH Cerkamed, Sandomierska, Poland) and 10 mL distilled water using the same needle as for NaOCl.

**Root Canal obturation**

Obturation was performed with Resilon/RealSeal sealer (Pentron Corp., Wallingford, US) using System B (SybronEndo, Glendora, USA) and Obtura III (Obtura Spartan,
Earth City, Missouri, US. A Resilon master cone (30/0.06) was selected and fitted to the canal length. The cone was accepted if “tug back” was felt. If the cone was loose, it was trimmed with scissors. The canals were dried using size 30 paper points (Diadent, Chungcheongbuk-do, Korea) and RealSeal primer was applied using a small brush. The sealer was applied to the master cone. A System B plunger (fine-medium size) at 150°C was inserted along the master cone to 5 mm short of the working length. Heat application was then stopped and light apical pressure was retained for 10 seconds. The plunger was withdrawn after application of a short heat burst. Obtura III at 150°C was used for backfilling using a 23 gauge needle tip. The coronal surface was light cured for 40 seconds. Five roots (2 central incisors, 2 lateral incisors, 1 canine) were obturated with master cones without the use of sealer to work as positive control.

All roots were stored for one week in a moist environment at 37°C.

Retreatment

The roots were randomly assigned into three groups:

Group 1 (n=30: 9 central incisors, 15 lateral incisors, 6 canines): no further treatment was performed.

Group 2 (n=30: 9 central incisors, 15 lateral incisors, 6 canines): the root filling material was removed using hand K-files.

Group 3 (n=30: 9 central incisors, 15 lateral incisors, 6 canines): the root filling material was removed using ProTaper retreatment files (Dentsply Maillefer, Ballaigues, Switzerland).
In groups 2 and 3, the coronal 2 mm of the filling was removed Gates-Glidden drills (sizes 2 and 3) (Dentsply Maillefer, Ballaigues, Switzerland), then two drops of eucalyptus oil (PPH Cerkamed, Sandomierska, Poland) were applied into the resulting space. In group 2, hand K-files were then used in a circumferential quarter-turn push–pull filing motion to remove the filling material. During removal, one or two drops of eucalyptus oil were applied as required. The final K-file size used was 30.

In group 3, Eucalyptus oil was used as in group 2. ProTaper retreatment D1, D2 and D3 files (at 500 rpm) were used to remove the filling material from the coronal, middle and apical thirds, respectively.

Retreatment was considered complete when no material was seen on the files or on the canal walls using magnification loupes (X2.5) (Orascoptic, Middleton, USA). The canals were irrigated with 3 mL 1% NaOCl, 5 mL 17% EDTA and finally with 10 mL distilled water. The root canals were re-obturated with Resilon using the technique described in the first treatment. The roots were stored at 37°C in a moist environment for one week.

The external surface of the roots, excluding the coronal aspect, was covered with two layers of nail varnish. Five roots (2 central incisors, 2 lateral incisors, 1 canine) were not retreated and totally covered (including the coronal surface) with the nail varnish to act as a negative control.

The roots were then immersed in 2% methylene blue dye at 37°C. Each group was divided into three subgroups (n=10) according to the immersion period: 1 day, 7 days and 30 days. The roots in the negative control were kept in the dye for 30 days.
At each time interval, the roots were removed from the dye and rinsed under running water. The roots were then horizontally sectioned using a diamond wheel saw at 2, 4, 6 and 8 mm from the coronal surface. After each sectioning, the root was rinsed with distilled water and air-dried to remove any debris. A stereomicroscope microscope (MEIJI Techno Co. Ltd., Tokyo, Japan) (x25) was used to examine the root for the presence of dye. According to the extent of dye penetration, a score was given for each sample:

Grade 0: No dye could be detected at the 2 mm section (no or <2 mm leakage).

Grade 1: Dye was detected at the 2 mm section but not detected at the 4 mm section (leakage <4 mm).

Grade 2: Dye was detected at the 4 mm section but not the 6 mm section (leakage <6 mm).

Grade 3: Dye was detected at the 6 mm section but not at the 8 mm section (leakage <8 mm).

Grade 4: Dye was detected beyond the 8 mm section (Leakage >8 mm).

Statistical analysis

SPSS Version 20.0 (IBM Corp., Armonk, US) was used to analyse the categorical data. The Kruskal-Wallis with multiple pair-wise comparisons was used to determine if there was any significant difference in dye penetration between the retreatment techniques and the time intervals for each group.
8.4 Results

Table 8.1 shows the number of samples in each group according to the extent of leakage. All of the positive control group were graded 4 at the first day and the negative control group had grade 0 at day 30. There was no significant difference in the extent of dye penetration for each root canal between all test groups at each time interval \((P>0.05)\). There was significant difference in the extent of dye penetration between the time intervals for each group \((P<0.001)\). Dye penetration increased significantly with time (Figure 8.1). Figure 8.2 shows a representative sample (from the no retreatment group after one week) viewed under magnification (x25) to measure the extent of dye penetration. The dye was visible at 2, 4 and 6 mm, but not at 8 mm section.

Table 8.1 Number of roots in each group according to the leakage scores.

<table>
<thead>
<tr>
<th>Score</th>
<th>No retreatment</th>
<th>retreated by Hand K-file</th>
<th>retreated by rotary ProTaper</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One day</td>
<td>One week</td>
<td>One month</td>
<td>One day</td>
</tr>
<tr>
<td>0</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>2</td>
<td>-</td>
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<tr>
<td>2</td>
<td>-</td>
<td>5</td>
<td>1</td>
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<tr>
<td>3</td>
<td>-</td>
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Figure 8.1 A line graph illustrates the increase in dye penetration with time in all groups.
Figure 8.2 A representative sample (from the no retreatment group after one week) visualized under magnification (x25) shows the dye (blue colour) could be clearly seen at 2 mm (A), 4 mm (B) and 6 mm (arrow) (C), but not at 8 mm (D). The sample was given a grade 3.
8.5 Discussion

The results of this study show that the retreatment techniques investigated (hand K-files and ProTaper retreatment files) had no significant effect on the leakage resistance of roots re-filled with Resilon. There was also no significant difference in the leakage resistance between the non-retreated and both retreated groups. Therefore, the null hypothesis was accepted. The sealing ability of Resilon has been previously investigated in primarily treated (48) and retreated teeth (315). However, no previous investigation has been performed to evaluate the effect of the retreatment technique on the sealing ability of Resilon.

Resilon can bond to methacrylate-based sealers which in turn bond to dentine to form a “monoblock” (28). The insignificant difference in leakage resistance between the non-retreated and retreated groups found in our study may be explained by the ability of Resilon to bond to dentine in retreated root canals as well as in primary treated roots. Similar results have been reported by Lin et al. (315) who also illustrated by the use of environmental scanning electron microscopy (ESEM) that Resilon formed resin tags in retreated roots.

Our study showed a significant increase in leakage with time in all groups. This is in agreement with previous studies (68, 71). Resin materials swell due to water absorption (plasticization) leading to deterioration in their mechanical properties (134). This may result in weakening of the bond between Resilon and dentine over time resulting in more leakage (142, 143).
Different methods have been used to evaluate leakage, including dyes (58, 92), bacteria (48), fluid filtration (189), an electrochemical technique (316) and radioactive isotopes (317). Although the clinical significance of dye penetration studies have been questioned (184, 318), previous studies reported a consistent correlation between dye penetration, which is the most popular method for evaluation of leakage (183), and other leakage evaluation methods (319). It has been reported that the dye leakage method is sufficiently valid provided that the experimental conditions such as type of specimen, type of dye and duration of immersion in the dye have been standardised (320). Previous dye leakage studies have described use of a vacuum to eliminate any air bubbles that might interfere with the dye penetration (321). However, it has been shown that there is no significant difference in the degree of dye penetration between vacuumed and non-vacuumed samples (322).

Visualisation of the extent of dye penetration has been performed using different techniques, such as clearing (92), longitudinal sectioning (57) and spectrophotometry (93). Clearing only allows detection of the dye between the filling material and the canal wall (320). Longitudinal sectioning can result in the plane of section missing dye penetration. Spectrophotometry, although allows quantitative assessment of dye (93), cannot detect leakage that has not reached the apical foramen. In the present study, we used horizontal sectioning of the root which is a recognised method (58, 320). Limitations of this method include loss of dentinal tissue and dye during sectioning, that some dyes are water soluble and thus may be affected by the water coolant. Also, sectioning only determines whether leakage is present or not in each section rather than giving a quantitative measurement (320). However, it does allow
visualization of dye penetration along the root canal wall and within the obturation material itself (320).

In conclusion, the current study showed that the leakage resistance of Resilon in retreated root canals is not different from that in the primary treatment and therefore, Resilon can be used to fill retreated root canals. It also suggests that Resilon would not withstand leakage over time if the coronal seal was lost. The retreatment technique has no significant effect on the leakage resistance of Resilon.
Chapter 9

General Discussion, Conclusions and Future Work Suggestions
9.1 General Discussion

Endodontic treatment has significantly advanced over the last decade; the introduction of different types of rotary instrumentation, use of magnification, and developments in root canal filling materials. An outcome of, and the stimulus for, such advances has been research, much of which has been directed towards obturation materials.

The ideal root canal filling materials should be biocompatible, sterile, radiopaque, dimensionally stable, easy to manipulate and remove for retreatment, have antimicrobial properties, provide a three-dimensional seal and not cause discolouration of the tooth (14). To date, no material has fulfilled all of these requirements.

Obturation of the root canal with a combination of gutta percha and a sealer is almost universally used. Gutta percha is considered to be the “gold standard” root canal filling material against which new materials are compared. Although gutta percha has many of the properties of the ideal filling material it has some deficiencies. While it is dimensionally stable, the sealer used with it is not. Resin-based sealers suffer from polymerization shrinkage (323), whereas zinc-oxide/eugenol-based, glass ionomer-based and calcium hydroxide-based sealers are soluble in tissue fluids (324). Therefore, a fluid-tight seal cannot be achieved especially if the coronal seal fails (197). In addition, gutta percha has no antimicrobial properties (325) and does not bond to any type of sealer (28).

In an attempt to overcome the previously stated shortcomings of gutta percha, other root filling materials have been introduced such as silicone-based systems
(GuttaFlow), glass ionomer-based systems (ActiV GP) and resin-based systems (RealSeal and EndoRez). In this dissertation, selected properties of the RealSeal system (Resilon) were investigated.

This thesis presents five experiments. The first two investigated properties of Resilon after obturation in primary treatment (quality of obturation and push-out bond strength) and the other three investigated some properties in endodontic retreatment (ease of removal, fracture resistance and leakage resistance).

The techniques and materials currently available for obturation result in fillings of variable quality. As is the case for gutta percha, Resilon can be placed in the canal using thermal techniques. In general, the literature shows that thermal obturation techniques produce a more homogenous filling than cold lateral condensation with fewer voids and better adaptation to the canal walls (7, 175, 178). The quality of obturation has been found to be one of the main predictors for the outcome of the endodontic treatment (273): the more voids in the filling, the more likely the filling is to have a poor prognosis. The presence of voids and gaps in the root canal filling provides a pathway through which micro-organisms and their toxins can gain access to the periradicular tissues and initiate or continue the inflammatory process.

The quality of obturation with Resilon using thermal obturation in comparison with gutta percha has been investigated (42). The method of evaluation involved sectioning the roots and examining them under a stereomicroscope. There are potential errors; some of the filling material might have been lost during sectioning and the chance of traversing a void is statistical and the shape of the voids may mean that volume fractions are not properly inferred from 2D sections. Hence, in the first
study (Chapter 4) of this research a highly accurate 3D analysis method, micro-CT, was used to investigate the volume of voids in the obturation materials. Resilon and gutta percha were compared using either cold lateral condensation or continuous wave of compaction techniques. The results indicated that the two materials resulted in filled canals with no significant difference in the percentage volume of voids. The technique of obturation was the important factor. The thermal obturation technique resulted in a more homogenous filling with a lower volume of voids than the cold lateral condensation technique. In cold lateral condensation, separate cones of the filling material are condensed in the canal with the use of a sealer on the canal wall and on each cone, whereas in the thermal technique, the softened material is packed into the canal in one increment after application of a sealer on the canal wall.

Much of the published work related to Resilon has been in vitro and to date, there is only one randomised clinical trial (131), which investigated the clinical outcome of obturation with Resilon compared with gutta-percha. The study assessed postoperative and recall radiographs (healed versus non-healed) and evaluated the clinical symptoms at recall appointments. It was found that the difference in the treatment outcome between the two filling materials was not statistically significant. This concurs with the results of the first study of this thesis, where the difference in the quality of obturation, which is one of the factors that affect outcome, between the two materials was found to be insignificant.

During analysis of the data and viewing the resulting 3D figures of the samples, it was noticed that the shape and position of the voids were different between the two obturation techniques (Figure 4.2). The voids were like channels between the cones of the filling material which were parallel to the long axis of the root in the samples.
obturated using cold lateral condensation. On the other hand, the voids were round and isolated within the filling material in the samples obturated using thermal obturation. The arrangement of the voids may have an effect on the speed of micro-leakage if the coronal seal is lost. Leakage via the filling material might be accelerated by the presence of voids parallel to the long axis of the root and connected like a channel.

One of the main advantages of Resilon over gutta percha is that it bonds to the dentine to form a “monoblock” (28). This is because of the dimethacrylate component which bonds to methacrylate-based sealers which in turn bond to the dentine (25). This bond can be affected by some materials used during root canal treatment such as sodium hypochlorite (157), chlorhexidine (239) and calcium hydroxide (240), which is the most commonly used intra-canal medicament (286). Other medicaments are also used, such as Vitapex and iodoform whose effect on the bond strength of Resilon has not been investigated and this was the aim of the second study (Chapter 5). The results of this showed that Vitapex and iodoform significantly reduced the bond strength of Resilon to dentine in comparison with Calcipast and Calcipast1. This may be due to the oil component of the Vitapex and iodoform which make it difficult to totally clean the canal of these medicaments.

The push-out test has been widely accepted as the best measurement of adhesion currently available (254). However, it has some limitations related to the diameter of punches used, sample orientation, modulus of elasticity of the filling material tested and the specimen thickness (254, 261). The punch diameter should be just slightly smaller than the canal diameter and not so small to puncture the filling material. The ratio between the pin diameter and the canal diameter should be less than 0.85. This
ensures that the stress concentration is near to the dentine-filling interface (254, 261). The angulation of the sample sectioning relative to the long axis of the root was found to have a little effect on the bond strength, but deviations of up to 10° resulted in great variations in the load profile (254). A correction factor $\sqrt{E_o / E_f}$ should be used in the formula to calculate the bond strength if the modulus of elasticity of the filling material is less than that of the dentine (261). The push-out formula works well for samples which are more than 1.1 mm thick (261).

When endodontic treatment fails, treatment is required. The options for treating failed root canal treated teeth are orthograde retreatment, retrograde surgical treatment or extraction. Orthograde re-root canal treatment is understood to be the treatment of choice in the first instance with the aim of eradicating the most common reason of failure, which is intra-radicular infection (192, 202). The first step in retreatment is removal of the previous filling material. It is important to totally remove the old filling so that the chemo-mechanical cleaning can reach any micro-organisms that may have remained or returned after completion of the first treatment (202).

Removal of the old filling material can be performed using several techniques, such as stainless steel or nickel-titanium hand files, nickel-titanium rotary files or ultrasonic instruments with or without the adjunctive use of solvents or heat (207, 209). The combined use of rotary and hand instrumentation has been advocated (21). The third study in this dissertation (Chapter 6) aimed to investigate the effectiveness of the use of hand K-files and ProTaper retreatment files in removal of Resilon in comparison with gutta percha placed into root canals by either cold lateral condensation or continuous wave of compaction technique using micro-CT. The
results of this study demonstrated that Resilon removal resulted in significantly more remaining material than gutta percha removal when thermal obturation technique was used. It was also found that the combination of hand K-file and ProTaper retreatment files was not more effective than ProTaper Universal alone in removal of the filling materials.

During endodontic treatment, tooth structure is removed to achieve straight line access to the root canal system. As tooth structure is removed, the tooth becomes weaker and may be subjected to fracture (100). Excessive forces during condensation of the filling material and the use of intra-radicular posts are other factors which increase the susceptibility of root fracture (263). Theoretically, filling materials which can bond to the root canal walls improve the root fracture resistance (25). As Resilon bonds to the root canal dentine, it would be expected that it increases the root fracture resistance (18, 28). In retreatment, any remaining material may act as a barrier and interfere with the bond between Resilon and root canal dentine and hence, reduces its root strengthening effect. The aim of the fourth study (Chapter 7) was to investigate the ability of Resilon to increase the fracture resistance of previously root canal treated teeth following retreatment using either hand K-files or ProTaper retreatment files. Regardless of the retreatment technique, the results showed that Resilon was not superior to gutta percha in terms of increasing the fracture resistance of the root after retreatment. The retreatment technique had no significant effect on the fracture resistance.

Several studies have reported that Resilon has the ability to strengthen the root in primarily treated roots (18, 103, 104), but others have found that it does not (106-108). In order for a material to strengthen the root, its modulus of elasticity has to be
similar or approximate to that of the dentine, so that the load stresses are evenly
distributed (25, 306). As the elastic modulus of Resilon is about 86.58 MPa (25),
which is far below that of the dentine (approximately 16,000 MPa) (117), it
undergoes plastic deformation under stress rather than absorbing or transferring the
stress (25). Therefore, the ability of Resilon to strengthen the root has been
questioned.

One of the main aims for the introduction of resin-based root canal fillings is to
provide a fluid-tight seal (28). Micro-leakage can result in re-infection of the root
canal system and failure of the endodontic treatment (191, 192). Following
retreatment, remaining material can interfere with the bond between Resilon and the
root canal dentine. This can prevent intimate contact and result in leakage if the
coronal seal is lost. In Chapter 8 of this thesis, the dye leakage resistance of Resilon
following retreatment was found to be not significantly different from primarily
treated roots. This may be explained by the ability of Resilon to bond to the dentine
in the presence of remaining material as well as in primarily treated roots (315). The
retreatment technique was found to have an insignificant effect on the leakage
resistance.

Sealability experiments have been criticised because their clinical implications are
not clear and the heterogeneity of the methods employed makes comparison difficult
(184, 281). However, they are still important to test any new material as they provide
an understanding of the ability of the material to seal the root canal space.

During examination of the root slices to detect the extent of dye leakage, it was
noticed that the longer the specimens remained in the dye, the deeper was the
penetration of the dye through the dentinal tubules. This may highlight the significance of providing a good coronal seal immediately after performing the endodontic treatment to prevent the deep penetration of micro-organisms through the dentinal tubules.

To summarise, obturation with Resilon showed no significant difference to obturation with gutta percha in terms of quality of obturation and fracture resistance in re-treated roots. Although it has been reported that both filling materials resulted in comparable treatment outcomes (131), more clinical trials are needed before Resilon is considered as a replacement for gutta percha, which has a well-recognised research record over years.
9.2 Conclusions

Within the limitations of this *in vitro* research, the following conclusions can be drawn:

- Filling the root canal with Resilon results in obturation with volume of voids insignificantly different from filling with gutta percha.

- The cold lateral condensation technique results in a filling with significantly more voids than the continuous wave of compaction technique regardless of the filling material used.

- The bond strength of Resilon is significantly reduced when the canal is medicated with Vitapex (oil-based CH+iodoform) or iodoform in comparison with CH or CH1 (aqueous CH+iodoform).

- Removal of Resilon for retreatment results in significantly more remaining material than gutta percha when continuous wave of compaction is used for obturation.

- When cold lateral condensation is used, significantly more remaining materials are left after retreatment in comparison with continuous wave of compaction.

- Removal of the filling materials for retreatment using combination of hand K-files and ProTaper retreatment files is not superior to ProTaper Universal files alone if the size of apical enlargement in retreatment, in relation with the primary treatment, is considered.

- Resilon does not have the ability to increase the root fracture resistance in primarily and previously root filled teeth in comparison with gutta percha, irrespective to the retreatment technique.
- Retreatment technique has no significant effect on root fracture resistance.
- Sealing ability of Resilon in retreated root canals is not significantly different from primarily treated ones.
- The retreatment technique has no significant effect on the leakage resistance of root canals re-filled with Resilon.
- Leakage through Resilon-filled and re-filled root canals increases significantly over time.
9.3 Suggestions for Future Work

The following aspects are suggested for further research:

1. The efficacy of Resilon needs to be investigated in vivo. Randomised clinical studies to assess the short and long term treatment outcome of teeth obturated with Resilon in comparison with gutta percha are required.

2. Investigation of the bond formation between Resilon and root canal dentine in the apical area of the root canal, where the application of the self-etch primer is difficult.

3. Clinical trials to evaluate the effect of remaining materials after removal of Resilon on the outcome of the endodontic retreatment.
References


71. Kokorikos I, Kolokouris I, Economides N, Gogos C and Helvatjoglu-Antoniades M. Long-term evaluation of the sealing ability of two root canal


77. Tay FR, Loushine RJ, Weller RN, Kimbrough WF, Pashley DH, Mak YF, Shirley Lai CN, Raina R and Williams MC. Ultrastructural evaluation of the

78. Kaya BU, Kececi AD and Belli S. Evaluation of the sealing ability of gutta-percha and thermoplastic synthetic polymer-based systems along the root canals through the glucose penetration model. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology 2007; 104:e66-e73.


105. Schafer E, Zandbiglari T and Schafer J. Influence of resin-based adhesive root canal fillings on the resistance to fracture of endodontically treated roots:


178. Peters CI, Sonntag D and Peters OA. Homogeneity of root canal fillings performed by undergraduate students with warm vertical and cold lateral


Appendix

Published Papers
Micro-CT Evaluation of Voids in the Filling Material of Single-Rooted Teeth Obturated with Different Techniques

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Abstract

The aim of this study was to compare the volume of voids in a resin-based root canal filling (Resilon) with gutta percha using either cold lateral condensation or continuous wave of compaction filling techniques using computed X-ray micro-tomography (micro-CT).

A total of 56 extracted upper anterior human teeth were decoronated, the canals shaped using rotary ProTaper files to a final size of F3 and randomly allocated into 4 groups (n=14) according to the filling material and obturation technique: Group 1: gutta percha/cold lateral (GP/C), Group 2: Resilon/cold lateral (R/C), Group 3: gutta percha/thermal (GP/T), Group 4: Resilon/thermal (R/T). Thermal filling was performed using System B and Obtura II. The filled roots were then scanned using micro-CT and the data were subsequently processed using Avizo 6.3 Standard version software. Statistical analysis was performed using the Kruskal-Wallis test with multiple pairwise comparisons.

The total percentage volume of voids in GP/C (2.40%) and R/C (1.88%) were significantly higher than GP/T (1.04%) and R/T (1.29%) (<0.001). A significantly higher percentage of voids was present in the coronal third compared with middle and apical thirds (P<0.001).

Thermal obturation resulted in a root filling with significantly fewer voids than the cold lateral condensation technique regardless of the obturation material used. Most of the voids located in the coronal third which emphasizes the importance of obtaining a good coronal seal following endodontic treatment.

Keywords: Computed tomography (CT); Resilon; voids.

Introduction

Optimal obturation leads to successful endodontic treatment (Ng et al. 2008). Incomplete filling of a well-cleaned and prepared root canal system could compromise the outcome of treatment (Ng et al. 2008). The ideal obturation material should provide good adaptation to the canal walls and fill any irregularities with the full length of the canal being densely filled with a homogenous mass of obturation material (Schilder 1967).

Gutta percha (GP) has been the material of choice for obturation for many years as it possesses favourable properties such as dimensional stability, good working properties, ease of removal, biocompatibility and radiopacity (Miner et al. 2006). One of the limitations of GP is that it does not bond to any type of sealer (Teixeira et al. 2004a). As many sealers shrink upon setting, there is a potential for gaps or voids creation via which microleakage may occur (Shipper et al. 2004; Wedding et al. 2007).

A resin-based material, Resilon, was introduced in 2004 (Teixeira and Trope 2004). It has been claimed that it bonds to the root canal dentine, strengthens the root when used as an obturation material, (Teixeira et al. 2004b; Skidmore et al. 2006; Hammad et al. 2007; Monteiro et al. 2011) and provides a better seal than GP (Shipper et al. 2004, Wedding et al. 2007). It has similar handling properties as GP and can be placed into root canals using either cold lateral condensation (Hammad et al. 2009; Santos et al. 2010) or thermal obturation (Epley et al. 2006; Karabucak et al. 2008).

Many properties of Resilon have been investigated such as leakage resistance (Shipper et al. 2004), root strengthening (Teixeira et al. 2004b, Hammad et al. 2007) and quality of obturation (Hammad et al. 2009). However, most of these studies relate to it when used with cold lateral condensation and very few have compared it with thermal obturation (Epley et al. 2006). As the use of heated filling techniques is increasing (Lee et al. 2009), investigation of the quality of obturation with Resilon using this method in comparison with cold lateral condensation is timely.

The few studies which have investigated Resilon using thermal obturation in comparison with cold lateral condensation have used a variety of assessment methods which may result in inaccuracies. In one study (Epley et al. 2006), the filled roots were sectioned and examined under a stereomicroscope. This process may lead to loss of some of the filling material and creation of space that may appear as voids. In the present study, micro-CT was used as it gives highly accurate three-dimensional analysis of voids (Jung et al. 2005).

The aim of this study was to compare the percentage volume of voids in root canals filled with Resilon and with GP using cold lateral condensation and continuous wave of compaction techniques. The null hypothesis was that there would be no significant difference in the percentage volume of voids between the four combinations of the two materials and obturation techniques.

Materials and Methods

This study was approved by the ethics committee at the University of Manchester (Reference number: UREC5-10275). Seventy upper anterior human teeth were collected, disinfected with 5% sodium hypochlorite (NaOCl) (Procter and Gamble, Weybridge Surrey, UK) for 10 minutes and stored in normal saline. Exclusion criteria were: roots that were carious, fractured, resorbed or immature. Roots with sclerosed canals, with more than one canal or those with root curvature >10°, as determined by Schneider (1971), were also excluded.

Preparation

From the initial sample, a total of 56 teeth (28 lateral incisors, 16 central incisors and 12 canines) were selected according to the aforementioned criteria. The teeth were decoronated and the length of the roots was reduced to 14 mm using a diamond wheel saw with water cooling (central
incisors, lateral incisors and canines were kept separate to facilitate in their allocation into groups for obturation. The working length was determined to be 1 mm short of the apical foramen using a size 10 K-file (VDW GmbH, Munich, Germany).

The root canals were prepared using rotary ProTaper files to the final size of F3 (Dentsply Maillefer, Ballaigues, Switzerland) and irrigated with 1% NaOCl. After completion of the preparation, the root canals were irrigated with 5 mL 17% ethylene-diamine-tetra-acetic acid (EDTA) (PPH Cerkamed, Sandomierska, Poland) and 10 mL distilled water.

**Obturation of Root Canals**

The roots were randomly allocated into four groups using a stratified sampling method (n=14: 7 lateral incisors, 4 central incisors and 3 canines) according to the filling material and obturation technique.

Group 1 (GP/C) was filled with ProTaper GP F3 (Dentsply Maillefer, Ballaigues, Switzerland) and AH-Plus sealer (Dentsply DeTrey GmbH, Konstanz, Germany) using cold lateral condensation. A master cone was selected and trimmed to fit the canal to the working length with tug-back. Then, the canal was dried using paper points (Diadent, Chungcheongbuk-do, Korea). The sealer was carried into the canal using the master cone. A finger spreader (Dentsply Maillefer, Ballaigues, Switzerland) was used to compact the GP cone and create a space for accessory points. When obturation was completed, the GP points were cut to the coronal end of the root using a heated instrument and the coronal part was compacted using a Machtou plugger (Dentsply Maillefer, Ballaigues, Switzerland).

Group 2 (R/C) was filled with Resilon/RealSeal (Pentron Corp., Wallingford, China) sealer using cold lateral condensation according to the manufacturers’ instructions. A Resilon point (30/0.06) was used as the master cone which was trimmed to fit the canal to the working length with tug-back. After drying the root canal with paper points, RealSeal primer was applied. RealSeal sealer was carried to the canal on the master cone. Cold lateral condensation was performed as previously described. The coronal surface was light cured for 40 seconds.

Group 3 (GP/T) was filled with ProTaper GP/AH-Plus sealer using a continuous wave of compaction technique. The sealer was carried to the canal using the master cone. A System B plugger of fine-medium size (SybronEndo, Glendora, USA) was selected and a rubber stopper was fitted 5 mm short of the working length marking the binding point. The heat source was adjusted to 200°C. The plugger was activated and used to cut the excess GP and then inserted into the canal along the master cone until the binding point was reached. The heat source was then deactivated and a firm pressure was maintained for 10 seconds. A one-second heat burst was activated and the plugger was withdrawn. The canal was then backfilled with GP pellets (Obtura Spartan, Earth City, Missouri, USA) using Obtura III at 200°C (Obtura Spartan, Earth City, Missouri, USA).

Group 4 (R/T) was obturated with Resilon/RealSeal sealer using the continuous wave of compaction technique described above. The temperature setting in System B and Obtura III was set to 150°C according to the manufacturers’ instructions.

All roots were stored for 72 hrs at 37°C and 100% humidity in air-tight containers.

**Scanning of the Roots**

The roots were scanned in a random order using a 225kV 3 μm source Nikon micro-CT housed in a walk-in enclosure (Nikon X-tek Systems Ltd., Tring, England). Using a sample-source distance of 2 cm and a detector-sample distance of 138 cm, magnified images were collected on a 2000 pixel (200 micron pixel pitch) detector allowing observation of fine differences in contrast. The X-ray attenuation could be adjusted by changing the target material and accelerating voltage. For this scan, copper was used as the target material. The
micro-CT settings were: 93 kV, 135 micro Amps, 1901 projections (radiographs), 1000 seconds exposure, gain 16.

The raw data were reconstructed using CTPro 3D software (Version XT 2.2, Metris, Hertfordshire, UK). A effective voxel size of 7.7-9.3 μm was obtained. Voids were observed in 2-dimensional (2D) (Figure 1) and 3-dimensional (3D) images (Figure 2) using Avizo 6.3 Standard version (Visualization Sciences Group, Berlin, Germany). A number of grey-scale thresholding values were tried and the upper and lower limit values demonstrated that the scatter per sample was found to be about 0.1% volume of voids. After segmentation, Avizo software was used to measure the total volume of voids. The percentage volume of voids was calculated using the following equation:

\[
\frac{\text{Total volume of voids}}{\text{Total volume of the canal}} \times 100
\]

**Statistical Analysis**

Test of normality showed that data were not normally distributed and therefore, non-parametric tests were used. Analysis of data was carried out using the Kruskal-Wallis test with multiple pairwise comparisons. The software used was SPSS Version 20.0 (IBM Corp., Armonk, US) with the level of significance set at 5%.

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**Figure 1. Visualization of Reconstructed Images Showing Virtual 2D Slices of the Filling**

(A) Gutta Percha/ Cold Lateral Condensation, (B) Resilon/Cold Lateral Condensation, (C) Gutta Percha/Thermal Compaction, (D) Resilon/Thermal Compaction. The Arrows Indicate Voids within the Filling Material and the Scale Bars are 5mm Long.
Figure 2. 3D Images of the Root Canal Fillings in (A) Gutta Percha/Cold Lateral Condensation, (B) Resilon/Cold Lateral Condensation, (C) Gutta Percha/Thermal Compaction, (D) Resilon/Thermal Compaction. The Blue Colour within the Filling Material Indicates Voids; the Scale Bars are 6–8mm Long.

Results

The means and standard deviations (SD) of the overall percentage (%) of voids are shown in Table 1. The GP/C (gutta percha/cold lateral) group showed the highest overall mean value (2.40%), whereas the GP/T (gutta percha/thermal) group had the lowest overall value (1.04%). The Kruskal-Wallis test indicated that there was a statistically significant difference between the groups (P<0.001). The multiple pairwise comparisons showed that Groups GP/C and R/C (Resilon/cold...
lateral) had significantly higher percentage of voids than Groups GP/T and R/T (Resilon/thermal) (P<0.001 for GP/C versus GP/T and P=0.007 for R/C versus R/T).

Table 2 shows the means and standard deviations of the percentage of voids in each third of the root canal. In the coronal and the middle thirds, the results were similar to those for the overall percentage of voids (GP/C and R/C showed significantly higher percentage of voids than GP/T and R/T) (P<0.05). In the apical third, there was no significant difference between the groups. When the thirds were compared for each group, the coronal third showed significantly higher percentage of voids than the middle third, which had significantly higher percentage of voids than the apical third (P<0.001). The percentage of voids in the coronal third in relation with the overall percentage of voids was 69.8% in GP/C, 75.5% in R/C, 70.2% in G/T and 73.7% in R/T.

Table 1. Means and Standard Deviations of the Overall Percentage of Voids

<table>
<thead>
<tr>
<th>Group (n=14)</th>
<th>Overall voids % mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP/C</td>
<td>2.40^a (0.66)</td>
</tr>
<tr>
<td>R/C</td>
<td>1.86^a (0.61)</td>
</tr>
<tr>
<td>GP/T</td>
<td>1.04^b (0.44)</td>
</tr>
<tr>
<td>R/T</td>
<td>1.29^b (0.44)</td>
</tr>
</tbody>
</table>

GP/C: gutta percha/ cold lateral condensation
R/C: Resilon/cold lateral condensation
GP/T: gutta percha/thermal compaction
R/T: Resilon/thermal compaction
Different superscript letters indicate statistically significant differences

Table 2. Means and Standard Deviations of the Percentage of Voids in Each Third of the Root Canal

<table>
<thead>
<tr>
<th>Group (n=14)</th>
<th>Coronal voids % mean (SD)</th>
<th>Middle voids % mean (SD)</th>
<th>Apical voids % mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP/C</td>
<td>1.65 (0.60)</td>
<td>0.66 (0.22)</td>
<td>0.09 (0.05)</td>
</tr>
<tr>
<td>R/C</td>
<td>1.42 (0.57)</td>
<td>0.44 (0.24)</td>
<td>0.02 (0.01)</td>
</tr>
<tr>
<td>GP/T</td>
<td>0.73 (0.30)</td>
<td>0.27 (0.20)</td>
<td>0.04 (0.03)</td>
</tr>
<tr>
<td>R/T</td>
<td>0.95 (0.40)</td>
<td>0.26 (0.12)</td>
<td>0.08 (0.06)</td>
</tr>
</tbody>
</table>

GP/C: gutta percha/ cold lateral condensation
R/C: Resilon/cold lateral condensation
GP/T: gutta percha/thermal compaction
R/T: Resilon/thermal compaction
The differences between the thirds in all groups are statistically significant. GP/C and R/C have significantly higher volume of voids than GP/T and R/T in the coronal and middle thirds.

Discussion

Traditional methods used to evaluate the quality of root fillings allow only partial evaluation of the root canal content. Radiographs give a two-dimensional view of a three-dimensional structure. Sectioning the roots to view them using a scanning electron microscope or a stereomicroscope could result in loss of some of the material which may mimic voids. Further, the chance of intersecting a void is statistical and the shape of the voids may mean that volume fractions are not properly inferred from 2D sections. The clearing technique is time consuming (Anbu et al. 2010) and the long periods of immersion in alcohol may affect the physical properties of gutta percha (Moller and Orstavik 1985). Recently, the use of


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computed tomography (CT) (Barletta et al. 2008; Kandaswamy et al. 2009; Anbu et al. 2010) and micro-CT (Zakizadeh et al. 2008; Roggenlof et al. 2010; Hatamleh and Watts 2011) in dental research has gained increasing popularity. It gives an accurate three-dimensional view of the root canal content without destroying the samples which can be used for further research (Hammad et al. 2009). In the present study, the voxel size obtained was 7.7-9.3 μm, which is better than that used in previously published studies (Hammad et al. 2009; Somma et al. 2011).

The null hypothesis was rejected as the results showed a statistically significant difference in the volume of voids between the tested groups. The cold lateral condensation technique with both materials showed a significantly higher percentage of voids in comparison with the thermal technique. This agrees with previous studies (Kandaswamy et al. 2009; Anbu et al. 2010; Peters et al. 2010) which compared the two techniques using gutta-percha. In cold lateral condensation, the resulting mass is not homogenous and there may be spaces present between the points. By contrast, the thermal technique produces a more homogenous mass with fewer voids and better adaptation of the filling to the canal walls (Anbu et al. 2010; Peters et al. 2010). However, during condensation with pluggers, air could be entrapped. None of our samples were void-free. This finding has also been reported in previous studies (Epley et al. 2006; Gulsahi et al. 2007; James et al. 2007).

Our study showed that the GP/C group had a higher percentage of voids than the R/C group, but this was not statistically significant. This is consistent with other studies (Gulsahi et al. 2007; James et al. 2007; Akman et al. 2010), but is in contrast with that found by Hammad et al. (2009). In the latter study (Hammad et al. 2009), the lowest percentage of voids was found in the GP group as compared with Resilon, GuttaFlow and EndoRez. The sealer used with GP was Tubliseal (a zinc-oxide eugenol-based sealer), whereas in the present study AH-Plus sealer (a resin-based sealer) was used. It has been reported that GP showed volumetric expansion when it came into contact with eugenol which resulted in a better seal of the obturation (Michaud et al. 2008). In addition, the voxel size used in the present study was lower than that used in the study by Hammad et al. (2009) which improved detection of smaller voids. This may explain the fewer voids in the GP group reported by Hammad et al. (2009).

In contrast with the findings of Hammad et al. (2009), the results of the present study showed that the coronal third in all groups contained a significantly higher percentage of voids than the middle and apical thirds. This may have a clinical significance if the coronal seal lost as it may accelerate penetration of fluids through the root canal filling and dissolution of the sealer. In both obturation techniques used in this study, the apical third of the canal was filled with a master cone. In the cold lateral condensation technique, the remainder of the canal was filled with accessory points which were packed using a spreader leading to a greater risk of void creation between the accessory points in the middle and coronal thirds as opposed to the apical third. Similarly, in the thermal obturation technique, the middle and coronal thirds were obturated with a softened filling material in which air bubbles may be entrapped during condensation. This may explain the significant difference in the percentage of voids between the thirds.

Voids inside the filling materials, which are not linked to the periphery of the filling, could be considered less clinically significant than peripheral gaps because micro-organisms, if present, are restrained in an unfavourable environment and do not have access to a nutritional supply. Peripheral gaps along the dentine-sealer or core material-sealer interfaces may jeopardize the outcome of root canal treatment (Ng et al. 2008). This is because they may act as a pathway that permits sealer dissolution and passage of micro-organisms through the filled root canal to the peri-radicular tissues. Furthermore, if residual micro-organisms remain trapped in the dentinal tubules after treatment is finished, the peripheral gaps may form.
channels through which the microorganisms can get access to nutrients and initiate or continue the inflammatory process.

This is an in vitro study and further in vivo investigations are indicated. Variations in the canal anatomy of the human teeth may affect the obturation quality. Ideally, contralateral teeth from the same individual should be used (De-Deus 2012). However, this is not practical in research settings and limits the sample size. Therefore, upper anterior teeth were used in this study and each group contained equal number of central incisors, lateral incisors and canines (stratified sampling). It would be beneficial in the future to extend the testing to a wider range of root curvatures as this would be more clinically relevant.

**Conclusion**

The results of the present study show that the percentage of voids in the fillings is low (1.04%-2.40%), regardless of the filling technique. However, the significant difference shown highlights the importance of the use of continuous wave of compaction technique in reducing the volume of voids in the root canal filling. In addition, the significantly higher percentage of voids in the coronal third in comparison with the middle and the apical thirds emphasizes the significance of obtaining a good coronal seal after completion of endodontic treatment.

**Acknowledgement**

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**References**


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Micro-CT evaluation of the effectiveness of the combined use of rotary and hand instrumentation in removal of Resilon

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This study compared the effectiveness of ProTaper rotary files with ProTaper retreatment and K-files in the removal of Resilon or gutta percha (GP) from canals filled either by cold lateral condensation or thermal obturation using micro-CT. Ninety-six teeth were prepared using ProTaper files and allocated into four groups (n=24): Group 1 was filled with GP/AX-Plus and Group 2 with Resilon/RealSeal using cold lateral condensation. Group 3 was filled with GP/AX-Plus and Group 4 with Resilon/RealSeal using System B and Obtura II. The roots were scanned by micro-CT. Each group was divided into two subgroups (n=12): A treated using ProTaper files and B, using ProTaper retreatment and K-files. The roots were scanned to calculate the volume of the remaining material. With thermal obturation, roots filled with Resilon had significantly more remaining material than GP. Obturation using thermal technique resulted in significantly less remaining material than cold condensation except Resilon retreated using ProTaper retreatment and K-file.

Keywords: Computed tomography (CT), Gutta percha, ProTaper, Retreatment, Resilon

INTRODUCTION

Peri-radicular diseases may persist or emerge following the completion of root canal treatment as a result of intra-radicular infection, extra-radicular infection or non-microbial factors. The main cause of failure is persistent, or recurrent microbial infection. Non-surgical retreatment is usually the preferred option for teeth in which endodontic treatment has failed as there is a greater opportunity to eradicate any intra-radicular source of infection compared with a surgical approach. Retreatment comprises removal of the old root filling material to allow access to any residual microorganisms and permit further cleaning and disinfection of the root canal system. Additionally, efficient removal of previous filling materials can facilitate intimate contact between the sealer and the root canal walls, thus potentially preventing microleakage.

Gutta percha is the most commonly used root canal filling due to its favorable properties such as dimensional stability, biocompatibility and ease of removal. However, it does not bond to sealer. A resin-based root canal filling, Resilon, was launched in 2004. It is capable of bonding to methacrylate-based sealers and as such may result in the prevention of microleakage and strengthening of the root treated tooth. Root filling materials can be removed by a variety of techniques such as the use of stainless steel or nickel-titanium hand files, nickel-titanium rotary files or ultrasonic instruments with or without the adjunctive use of solvents or heat. Studies have compared the effectiveness of either rotary to hand instrumentation or different rotary systems. The combined use of hand instruments and rotary files for effective removal of filling materials has been advocated, but no study has investigated the effectiveness of a combination of the two.

Several studies have investigated the ease of removal of Resilon compared with gutta percha. So far, however, there has been no published data related to the relationship between removal success and method of filling technique (i.e. cold lateral condensation versus thermal obturation).

The aim of this study, therefore, was to investigate the effectiveness of rotary instrumentation and its combination with hand instrumentation in the removal of gutta percha and Resilon placed into root canals by either cold lateral condensation or continuous wave of compaction technique using micro-CT. The null hypothesis was that there would be no significant difference in the removability between the tested materials, techniques of obturation and techniques of removal.

MATERIALS AND METHODS

Ethical approval for this study was obtained from the Ethics Committee at the University of Manchester (URECS-10215). Upper anterior human teeth were collected, placed in 5% sodium hypochlorite (NaOCl) for 10 min and then stored in normal saline. Examination of the roots was performed under magnification (×40) to exclude roots with cracks, fracture, resorption, caries or immature apices or those with a root curvature of more than 10°, as described by Schneider.

Preparation of teeth

Ninety-six upper anterior teeth (48 central incisors, 24
lateral incisors and 24 canines) were selected according to the criteria noted above. Teeth were decoronated and root lengths were reduced to 14 mm using a diamond wheel saw with water cooling (Model 650, South Bay Technology Inc., California, USA). Central incisors, lateral incisors and canines were kept separate to facilitate in their allocation into groups for obturation. The working length was determined to be 1 mm short of the apical foramen using a size 10 K-file (Quality Endodontic Distributors Ltd., Peterborough, UK). A glide path was established and the canals were prepared using rotary ProTaper Universal files (Dentsply Maillefer, Ballaigues, Switzerland) to size F3. The motor used was an X-smart (Dentsply Maillefer, Ballaigues, Switzerland) with a contra angle hand-piece. The canals were irrigated with 1 ml 1% NaOCl (Proctor and Gamble, Weybridge, Surrey, UK) after each filing. When the preparations were completed, the root canals were irrigated with 5 ml 17% ethylene-diamine-tetra-acetic acid (EDTA) (Eph Seramex, Sandomierzka, Poland) and 10 ml distilled water.

Obluration of root canals

The roots were randomly allocated into four groups using stratified sampling (n=24, 12 central incisors, 6 lateral incisors and 6 canines) based on the material and technique of obturation:

Group 1 (G1) was filled with ProTaper gutta percha/Gutta-Plus sealers (Quality Endodontic Distributors Ltd., Peterborough, UK) using cold lateral condensation. A suitable master cone (fitted the canal to the working length with tug-back) was selected and the canal was dried using paper points. The sealer was applied using the master cone. A finger spreader (Dentsply Maillefer, Ballaigues, Switzerland) was used to compact the cone and accessory points were inserted into the resulting space until obturation was completed. The gutta percha points were cut to the coronal end of the root using a heated instrument and the coronal part was condensed using a blacktop plugger (Dentsply Maillefer, Ballaigues, Switzerland).

Group 2 (G2) was filled with Resilon/RealSeal (SybronEndo, Glendora, USA) sealer using cold lateral condensation. A master cone of size 30/0.06 was selected. RealSeal primer was applied and the excess was removed using paper points. The sealer was applied using the master cone. Lateral condensation was completed as described for Group 1. The canal surface was light cured for 40 s as recommended by the manufacturers.

Group 3 (G3) was filled with ProTaper gutta percha/Gutta-Plus sealer using continuous wave of compaction technique. A System B plugger of fine-medium size (SybronEndo, Glendora, USA) was used and a rubber stopper was adjusted to 5 mm short of the working length. The temperature was set to 200°C in the touch mode. The excess GP was cut using the hot plunger which was then inserted alongside the master cone until the rubber stopper reached a reference point. The heat application was then stopped and apical pressure was maintained for 10 s. The plugger was withdrawn after one-second activation of the heat source. Backfilling was performed using Obtura III at 200°C (Quality Endodontic Distributors Ltd., Peterborough, UK).

Group 4 (G4) was obturated with Resilon/RealSeal sealer using System B and Obtura III as explained for Group 2. Temperature in System B and Obtura III was set to 150°C according to the manufacturers’ instructions. All roots were stored in air-tight containers for a week at 37°C and 100% humidity. All the root fillings were carried out by one operator.

Scanning of the roots

Teeth were scanned in random order using a Nikon micro-CT (225 kV, 3 μm source) (X-Tek Systems Ltd., Ting, England) housed in a customised bay. Images were collected on a 2,000 pixel detector using a sample-source distance of 2 cm and a sample-detector distance of 136 cm which allowed observation of fine differences in contrast. The target material could be changed which allowed adjustment of the X-ray attenuation by accelerating voltage. Copper was chosen as the target material. The micro-CT settings were 50 kV, 130 micro Amps, 1991 projections (radiographs), 1000 s exposure, gain 16.

Retreatment

Each group was divided into two subgroups (n=12, 6 central incisors, 3 lateral incisors and 3 canines). In both subgroups, the coronal 2 mm of the filling was removed using Gates Glidden drills (3 and 4) (Quality Endodontic Distributors Ltd., Peterborough, UK). Then, two drops of eucalyptus oil (Eph Seramex, Sandomierzka, Poland) were placed in the space made available. In subgroup A, the filling material was removed using rotary ProTaper Universal files (F1, F2 and F3) (at 300 rpm) and in subgroup B using rotary ProTaper Universal retreatment files (D1, D2 and D3) (Quality Endodontic Distributors Ltd., Peterborough, UK) (at 500 rpm per the manufacturer’s recommendation) followed by hand K-files (25 and 30). ProTaper Universal and retreatment files were used at the following penetration depths: F1 and D1 to the coronal third, F2 and D2 to the middle third and F3 and D3 to the apical third. In subgroup B, hand K-files (25 and 30) were used to the full working length in a circumferential quarter-turn push-pull motion. The criterion for completion of the treatment was clean canal walls and no material on the files as observed by the naked eye. When retreatment completed, irrigation was performed using 5 ml 1% NaOCl, 5 ml 17% EDTA and finally, 10 ml distilled water. Root canals were dried using paper points. All the retreatment work was carried out by one operator.

Scanning of the roots

The Nikon micro-CT was used to scan the roots for the second time using the same settings as for the first scan. The raw data from the first and second scans were reconstructed using CTPro 3D software (Version XT 2.2, Metro, Hertfordshire, UK). A voxel size of 7.7×7.7×9.3 μm was obtained. Using Avizo 6.3 Standard version
(Visualization Sciences Group, Berlin, Germany), the total filling and the remaining material were viewed in three-dimensional images. The total volume of filling was measured from the data of the first scan and the total volume of the remaining material from the second scan. The percentage of the volume of the remaining material was then calculated.

**Statistical analysis**

SPSS Version 20.0 (IBM Corp., Armonk, US) was used with the level of significance set at \( p < 0.05 \). Data were found to be not normally distributed and therefore, non-parametric tests were used. Analysis of data was carried out using Kruskal-Wallis test with multiple pairwise comparisons.

**RESULTS**

Table 1 shows means and standard deviations of the overall percentage volume of remaining material. Resilon/cold lateral group (C/L) retrieved using ProTaper Universal rotary files showed the highest percentage volume of remaining material (3.94%) and gutta percha/thermal group (GP/T) retrieved using ProTaper Universal rotary files showed the least percentage (1.34%). When the thermal obturation technique was used, teeth filled with Resilon were found to have significantly more remaining material than gutta percha when they were removed using ProTaper Universal retreatment files and hand K-files \( p=0.028 \) and using ProTaper Universal files \( p=0.013 \). There was no significant difference between Resilon and gutta percha when the cold lateral condensation technique was used.

On comparison of the techniques of obturation, the continuous wave of compaction resulted in significantly less remaining material than the cold lateral condensation technique in all groups except the Resilon group retreated using ProTaper Universal retreatment files and hand K-files \( p=0.004 \) for the gutta percha group retreated using ProTaper Universal files and \( p=0.018 \) for the Resilon group retreated using ProTaper Universal files. There was no significant difference between the treatment techniques used. As shown in Table 2, the remaining material in the apical third was found to be significantly more than in the middle and the coronal thirds in all groups. Figure 1 illustrates reconstructed three-dimensional images for a representative sample filled with gutta percha before and after retreatment.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Means and standard deviations (SD) of the overall percentage volume of remaining material in the tested groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Filling/Retreatment technique</td>
</tr>
<tr>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Cold lateral condensation</td>
<td>2.80 (0.57)</td>
</tr>
<tr>
<td>Continuous wave of compaction</td>
<td>1.94 (0.53)</td>
</tr>
</tbody>
</table>

P: ProTaper Universal files, PH: ProTaper retreatment files and hand K-files. The two obturation techniques are significantly different except with Resilon when removed by PH. Resilon is significantly different from gutta percha when continuous wave of compaction technique used irrespective to the removal technique.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Means and standard deviations (SD) of the percentage volume of remaining material in each third of the root canal in the tested groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Filling/Retreatment technique</td>
</tr>
<tr>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Cold lateral condensation</td>
<td>Coronal</td>
</tr>
<tr>
<td>Middle</td>
<td>0.65 (0.32)</td>
</tr>
<tr>
<td>Apical</td>
<td>1.95 (0.50)</td>
</tr>
<tr>
<td>Continuous wave of compaction</td>
<td>Coronal</td>
</tr>
<tr>
<td>Middle</td>
<td>0.18 (0.08)</td>
</tr>
<tr>
<td>Apical</td>
<td>1.11 (0.31)</td>
</tr>
</tbody>
</table>

P: ProTaper Universal files, PH: ProTaper retreatment files and hand K-files. The apical third is significantly different from the other two thirds in all groups.
DISCUSSION

The present study showed that when Resilon was removed significantly more material remained than in teeth filled with gutta percha when a continuous wave of compaction technique was used. It was also found that obturation using the cold lateral condensation technique resulted in significantly more remaining material than the continuous wave of compaction technique after removal in all groups except the Resilon group retreated using ProTaper Universal retreatment files and hand K-files. Removability of Resilon in comparison with gutta percha has been previously investigated using different retreatment techniques. However, no study has compared the outcome of removal of the two root filling materials when placed into the canal using different techniques. In addition, the effectiveness of the combined use of hand and rotary instrumentation has not been examined before. Very few studies have used micro-CT to measure the volume of the remaining material. In this study, micro-CT was used as it gives an accurate three-dimensional image of the remaining material.

Resilon matrix is composed of co-polymers of polyurethane and urethane dimethacrylates. The dimethacrylate component enables Resilon to be bonded to various dual-cure methacrylate-based resin sealers which in turn bond to the root canal dentine forming a "monolithic" structure. By contrast, gutta percha, which is composed of zinc oxide and gutta percha, does not bond to any type of sealers. This may explain the significantly greater volume of Resilon remaining compared with gutta percha found when the thermal obturation technique was used. Similar results have been reported in previous studies, but contradictory results have also been found. It has been reported that complete setting of RealSeal sealer takes about 30 min in an anaerobic environment, but may take one week in an aerobic field. In the study by Rammel et al., the time allowed for the sealing to set was 72 h, whereas in this study, the roots were stored for a week. Therefore, the low volume of Resilon reported in the former study may be attributed to the incomplete setting of the sealers.

But why was the difference between Resilon and gutta percha significant only with the thermal obturation technique and not with the cold lateral obturation technique? It has been reported that softened Resilon flows better than gutta percha into lateral canals. Therefore, there would be more residual Resilon than gutta percha in the lateral canals after removal. In addition, it has been found that eucalyptus oil is more effective on the thermoplastic gutta percha than conventional gutta percha and this may explain the results obtained in this study.

It was found that obturation using cold lateral condensation resulted in significantly more residual material than the continuous wave of compaction after removal in all groups except the Resilon group retreated using ProTaper Universal retreatment files and hand K-files. The latter technique may require a smaller quantity of sealer and form a more homogeneous mass than the former. Hence, there would be a lesser amount of sealer to be eliminated and easier removal of the homogenous mass. When ProTaper Universal retreatment files and hand K-files were used, the difference between the two obturation techniques with Resilon was not significant. This may be attributed to the equal effectiveness of this technique in removal of Resilon with both obturation techniques. Previous studies which compared the effectiveness of hand with rotary instrumentation reported contrasting results. This may be due to differences in the rotary systems tested, type of hand file and time allowed for setting of sealers. The current study found no significant differences in the effectiveness of removal between ProTaper Universal rotary files and the combined use of ProTaper Universal retreatment files and hand K-files.

The retreatment in the ProTaper Universal groups was performed up to a file size 15, whose tip size is 30, and to size 30 hand K-file in the combined ProTaper Universal retreatment files and hand K-files groups. The standardization of the size of the apical enlargement may explain the insignificant difference found.

The results of this study showed that the remaining material in the apical third was significantly more than the middle and coronal thirds in all tested groups. This was in agreement with previous studies which investigated different retreatment techniques. During retreatment, the material in the coronal and middle thirds is more accessible via both mechanical and chemical removal techniques than the material in the apical third. In addition, the material may be pushed to the apical third during removal. Furthermore, the root
canal anatomy in the apical third is complicated with lateral canals and ramifications which make complete removal of the filling material very difficult. Micro-CT was used in this study as it has been shown that it gives a highly accurate, non-destructive, three-dimensional view of the internal structure of the root.

Variations in the anatomy of the human teeth such as lateral canals and other root canal ramifications may influence the removal of the filling material. However, the roots were randomly allocated into groups and therefore they were equally affected. As this is an in vitro study, caution should be exercised when these results are extrapolated to a clinical situation. The percentages of the remaining material shown in this study, although significantly different, are actually small (1.34–3.94%) and clinical studies are needed to see if these differences are clinically significant.

CONCLUSION

The current findings show that re-treatment of teeth filled with Resilon resulted in more residual material than those filled with gutta-percha when a thermal compaction technique was used. This may highlight the need for meticulous care if this root-filled root filling material needs to be removed. Removal of Resilon and gutta percha from teeth filled using cold lateral condensation resulted in more residual material than those filled using thermal compaction. The combined use of rotary and hand instrumentation may not be superior to rotary instrumentation alone if the size of apical enlargement in retreatment, in relation with the primary treatment, is considered.

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REFERENCES

study: Int Endod J 2010; 43: 64-68.


