CHAPTER SIX

DISCUSSION

6.1. Methodology

6.1.1. Tooth collection

A number of media have been used in different studies for the storage of extracted teeth. These include formalin, thymol, chloramine T trihydrate, sodium azide, saline, water and others (Hilton et al., 2002). In the present study, teeth were disinfected using 0.5% chloramine for one week, the maximum period recommended by ISO (ISO/TS11405:2003). It is a bacteriostatic and bactericidal solution. Teeth were then stored in distilled water at 4ºC. Distilled water was changed regularly every week in order to prevent deterioration. No other chemical agent was added afterwards as advised by ISO (ISO/TS11405:2003).

6.1.2. Root canal preparation and irrigation

6.1.2.1. Root canal preparation

Morgan and Montgomery (1984) reported that the crown-down preparation technique efficiently cleaned and shaped the root canal, with minimum extrusion of debris through the apical foramen. Crown-down instrumentation was used in this study due to its many advantages over the step-back technique, as outlined by Carrotte (2004), as follows:

1. Enhanced volumes of irrigant can be placed quickly compared with other methods of instrumentation, such as the classic “Step-Back” technique.
2. Better tactile sense is possible because restrictive dentine is removed coronally, allowing the operator better control of files.
3. Enhanced debris removal is possible due to greater volume of irrigant.
4. Less instrument fracture and less risk of compacting debris apically which may block the canal.
5. More rapid instrumentation.

Ruiz-Hubard (1987) also demonstrated a better performance of the crown-down technique compared to the step-back preparation technique. Several studies have attempted to quantify the amount of debris extracted beyond the apical foramen (Ruiz-Hubard et al., 1987; Swindle et al., 1991; Al-Omari and Dummer, 1995; Ferraz et al., 2001). Al Omari and Dummer (1995) instrumented 208 artificial canals using eight different hand instrumentation techniques and found that balanced force and crown-down techniques extruded the least amount of debris. Barbizam et al. (2002) reported the superior results of root canal cleanliness with the manual crown-down pressureless technique compared with ProFile 0.04 rotary instrumentation for preparation of lower anterior incisors with flattened roots (in cross section). The concept behind circumferential filing is that a small file can move around the oval canal on the outstroke and contact the whole canal wall without the risk of mesial or distal perforation (Wu et al., 2003b).

The enhanced taper in the apical third of the root canal provides resistance against the pressure of obturation and acts to prevent the extrusion of the filling material during obturation (Serota et al., 2003). Apical patency refers to the ability to pass a small K-file through the apical foramen at all times during the preparation procedure to ensure that dentinal debris, otherwise known as “dentine mud” does not accumulate and become the source of future iatrogenic and negative events. These events can include separated files, canal transportation, and pulp debris that can percolate into the apical tissue causing inflammation and ultimately apical infection. It was also thought to reduce the potential of forming a plug of infected dentinal debris in the apical zone (Buchanan, 1989). Thus, in this study apical patency was maintained throughout canal preparation to minimize these events.

However, the concept of patency still remains as one of the major controversies in root canal treatment. One reason for not advocating apical patency is the possibility of increased extrusion of debris and filling materials to the periapical tissues (Ricucci and Langeland, 1998).

6.1.2.2. Irrigation protocol

Irrigation has an important role during endodontic treatment. A number of authors have proposed a sequence using different irrigating agents in order to achieve the best chemical preparation (Chivian, 2004; Shipper et al., 2004b; Teixeira et al., 2004a; Epley et al., 2006). It is generally accepted in endodontic practice that sodium hypochlorite (NaOCl) is the most suitable solution for irrigation of the root canal system, because it has many desirable qualities and properties which include bactericidal action, dissolution of organic material and minor lubrication (Barnard et al., 1996). However, NaOCl by itself is not sufficient for total cleaning of the root canal system (Ayhan et al., 1999). It has no effect on the smear layer and its high surface tension does not allow for its cleaning and disinfection of the root canal system totally. Also, the greater the dilution, the less effective is the solution at dissolving organic debris in the root canal system. Ayhan et al. (1999) reported the antimicrobial effects of various endodontic irrigants on selected microorganisms and observed that 5.25% NaOCl was superior and a lower concentration of NaOCl (0.5%) resulted in significantly decreased antimicrobial effectiveness. In the present study, the concentration of NaOCl was 5.25% because this concentration was found to be more effective in dissolving necrotic tissue (Hand et al., 1978; Ayhan et al., 1999) than lower concentrations.

Before obturation of the root canal system, removal of the smear layer is mandatory for sealers to penetrate into the dentinal tubules. Ethylenediaminetetraacetic acid (EDTA) solution is generally accepted as the most effective chelating agent with lubricant properties and is widely used in endodontic therapy (Çalt and Serper, 2002). EDTA at 15-17% concentration, is effective in demineralizing dentine (ỚConnell et al., 2000; Çalt and Serper, 2002), and can be used to remove the smear layer (Goldman et al., 1981; ỚConnell et al., 2000; Çalt and Serper, 2002). SmearClear™ is a combination of EDTA and a surfactant to enhance flotation (Averbach and Kleier, 2006), that allows a greater degree of wetting of the canal walls and deeper penetration of the solution, hence a greater potential for adhesion of the sealer to create mechanical locks of resin into tubules as claimed by the manufacturer.

Teixeira et al. (2005) studied the effect of application time of EDTA and NaOCl on intracanal smear layer removal. They found that canal irrigation with NaOCl and EDTA for 1, 3 and 5 minutes were equally effective in removing the smear layer from the canal walls of straight roots. In this study, NaOCl and SmearClear™ were left in the canal for 1 minute as recommended by the manufacturer.

However, NaOCl had been shown to adversely affect the bond strengths of composite resins to dentine after root canal treatment (Ozturk and Özer, 2004). Furthermore, residual chemical irrigants are likely to diffuse into the dentine and dentinal tubules and may contaminate the surface, which may in turn affect the penetration of resin into the dentine structure or the polymerization of the monomer (Erdemir et al., 2004). For these reasons, the root canals were rinsed finally with distilled water to ensure complete removal of the NaOCl residue. Also, absolute alcohol is not needed because the RealSeal™ sealer is hydrophilic according to the manufacturer.

6.1.3. Pilot study

A pilot study was undertaken to ascertain the feasibility and difficulty of various techniques to prepare and obturate the human root canal system.

The techniques for root canal preparation and obturation were practised extensively beforehand. All specimens were prepared and filled by one operator to reduce interoperator variability. In order to reduce the possibility of deformation or fracture of instruments (K- files and Gates-Glidden drills), each instrument was used to prepare only five root canals in the main study. In order to standardize the lateral compaction technique (LC), 8-10 accessory filling core materials (gutta-percha and RealSeal™) were used in each canal.

The use of non-standardized finger spreaders and matching filling points from different manufacturers was not advised due to differences in dimension and degrees of taper found between them (Briseňo Marroquin et al., 2001). Hartwell et al. (1991) showed that lack of uniformity between gutta-percha and the finger spreader resulted in an unfilled space. If a finger spreader was narrower than the following gutta-percha cone, or if a finger spreader was too large, an unfilled space remained laterally around the following cone. In the current study, measurements of the finger spreaders and filling core materials showed correlation for the same manufacturer. Thus, medium-size non-standardized filling cores of RealSeal™ (SybronEndo, Orange, USA) and gutta-percha (Kerr/SybronEndo, USA) together with medium-size Kerr finger spreaders (Kerr/SybronEndo, USA) were used.

6.1.4. Evaluation method

Assessment of the quality of a root canal filling by cross-sectional analysis of the space occupied by filling core materials, sealer and voids has been advocated by a number of authors (Silver et al., 1999; Wu et al., 2000c, 2001b; Gordon et al., 2005; Keçeci et al., 2005; De Deus et al., 2006). The aim of obturation is to have the maximum amount of filling core material in the canal space to reduce the potential for gaps that occur due to sealer contraction or dissolution. Gutta-percha is dimensionally stable whilst the sealer can dissolve over time (Peters, 1986). Sealer thickness and the filling core material component may be of particular relevance when the apical root filling is analyzed. The apical root filling should provide a seal, especially because after post-space preparation, only the apical root filling of 3-4 or 4-5 mm in length remains (Wu et al., 2002b). Various investigators have found the apical root canal to be less clean than the middle and coronal portions of the root canal (Littman, 1977; Wu and Wesselink, 1995). This suggests that bacteria remain in the apical part of the canal. If root fillings fail to ensure a long-term seal, seepage of tissue fluids may provide the residual bacteria with a nutritive substrate, and the growth of the remaining bacteria in the apical root canal may cause the persistence of the periapical lesion (Molander et al., 1998). Moreover, studies have shown that numerous lateral canals are present in the apical third of the root. Rubach and Mitchell (1965) detected lateral canals in 45% of the 74 teeth they studied, the majority of them located in the apical third. De Deus (1975) found lateral canals in 27.4% of 1140 teeth: in 17.0% of the teeth, they were located in the apical third, in 8.8% in the middle third and in 1.6% in the coronal third. In this study, the first section, L1 (1 mm) and second section, L3 (3 mm) were, arguably, the most critical areas for evaluation of obturation quality for the above reasons.

A critical problem associated with tooth sectioning was the plasticization of the obturation material which could distort the root filling and affect the result. Therefore, to overcome this problem, the cross-section cuts were made by using a copious flow of cold water to minimize the smearing of filling materials (Eguchi et al., 1985; Wu et al., 2001b; Keçeci et al., 2005).

Low-vacuum scanning electron microscopy allows the examination of moist specimens without preparation or coating so that specimens may be viewed in near *vivo* conditions. This method virtually eliminates surface charging problems experienced in highvacuum scanning electron microscopy, extending imaging to samples difficult to examine or incompatible with conventional scanning electron microscopy methods (Wight and Zeissler, 1993). Back-scattered electron imaging was used in low-vacuum SEM to improve contrast, thereby facilitating measurement. Moreover, low-vacuum scanning electron microscopy is a relatively inexpensive alternative, which has a number of potentially useful applications in the biomaterials research field (Shipper et al., 2004a).

6.1.5. Root canal sealer

A wide variety of root canal sealers are commercially available and there is no consensus on which material seals most effectively. In the current study, AH-Plus™ sealer was used with gutta-percha in the control group due to its excellent properties, such as low solubility, small expansion, adhesion to dentine, very good sealing ability, little shrinkage, radioopacity and good tissue compatibility. Moreover, certain disadvantages of AH-26 such as a tendency to discolouration and the release of formaldehyde have been eliminated in AH-Plus™, a claim made by the manufacturer. Also, another advantage of AH-Plus™ is its application form: a paste-paste system, which ensures rapid and clean mixing.

6.2. Results

6.2.1. Time taken for obturation

Time taken for obturation is only one of the many criteria used to compare materials and techniques. A speedy method may lead to less operator and patient fatigue. In the present study, the time taken for obturation using the warm vertical "continuous wave" technique (WVCW) and warm vertical compaction of injected filling materials (WVCI) was significantly shorter than the time taken using the lateral compaction technique (LC) for both materials (RealSeal™ and gutta-percha). There was no significant difference in obturation time for both materials using the same technique. These results agree with many previous studies (Buchanan, 1996; Silver et al., 1999; Keçeci et al., 2005), who reported that the time taken for the warm vertical "continuous wave" technique (WVCW) was shorter than that taken for the lateral compaction technique (LC). The mean time reported in the present study was much longer than the time reported by Buchanan (1996), but substantially less than for the lateral compaction technique (LC).

6.2.2. Extrusion of filling materials

Schilder (1967) mentioned that the apical end of the root canal should be kept as small as practical in order to obtain a good seal and prevent extrusion of filling materials. It is important that prior to obturation, the canals should be debrided and prepared up to the cementodentinal junction. Over-instrumented canals produce severe inflammatory reaction which is different from overfilling, where the filling material passes through the apex accidentally. The clinical importance of overfilling is not only due to material irritation, but also due to the lack of an apical seal (Seltzer et al., 1973). A large volume of sealer at the apical part of the canal leads to apical leakage over longer periods (Pommel and Camps, 2001b). Kuttler (1955) advocated that healing would be better, when the root canal filling is short of the apex. Eransquin and Muruzábal (1968) were of the views that overfilling leads to necrosis of the area adjacent to the periodontal ligament because of infarct due to obstruction of the vessels in the apical areas. Davis et al. (1971) have reported that fillings which appeared flush with the apical foramen were usually overfilled and produced severe inflammatory reactions. Binnie and Rowe (1974) observed in their study that there was an increased chance of epithelial proliferation and cyst formation with overfilled teeth in dogs. In the case of overfilling, initial inflammatory reaction which sets in, can lead to the start of the healing process. The overfilled gutta-percha is encapsulated later by the defense cells of the body, depending upon the individual resistance. Yared and Bou Dagher (1994) observed that canals prepared to a size 40 file resulted in significantly more overextensions than those prepared to a size 25 file, using the warm vertical compaction technique.

Recently, Resilon™ was used *in vivo* in dogs (Shipper et al., 2005). The amount of apical periodontitis, as determined by inflammation, was assessed. All inflammation seen was mild, and there was less inflammation seen in the teeth obturated with the Resilon™ system compared to the group using AH-26 and gutta-percha. Versiani et al. (2006) showed that the reduced apical periodontitis observed clinically by Shipper et al. (2005) was due to the release of calcium ions from the Epiphany™ sealer. Release of calcium ions has been shown to favour a more alkaline pH of the environment leading to biochemical effects that culminate in the acceleration of the repair process (Seux et al., 1991). No mention was made in the study by Shipper et al. (2005) of any extrusion of sealer through the apex. However, any sealer extruded through the apical foramen may not set completely in periradicular tissues due to the presence of oxygen. Oxygen is known to inhibit vinyl polymerization in resins used in restorative dentistry (Franco et al., 2002). Resin materials do not undergo complete polymerization, and about 40-60% of the carbon remain unsaturated (Finger et al., 1996). The degree of conversion in resins represents the percentage of double bonds of molecules in the resin, such as Bis-GMA, that react (Craig, 2002). The degree of conversion is generally higher for photo-initiated or dual cure polymerization (Craig, 2002). The molecules that do not react are a potential source of toxicity. However, until now, no study has been performed to evaluate the response of the periradicular tissues to extruded Resilon™.

There was no attempt to gauge the width of the apical constriction in this study. The present study with canals prepared to a size 35, showed that extrusion was more common in the warm vertical "continuous wave" technique (WVCW) than in the lateral compaction technique (LC) regardless of the materials that were used. The higher occurrence of apical extrusion of fillings in warm compaction techniques is consistent with other *in vitro* investigations (Yared and Bou Dagher, 1994; Al-Dewani et al., 2002; Keçeci et al., 2005). Furthermore, with regard to the deeper penetration of the plugger to 3-4 mm from the working length, several practical problems may arise in a clinical setting. One is the tendency for the softened filling core materials to extrude through the apical foramen. However, Wu et al. (2002b) showed that extrusion of gutta-percha is independent of the depth of heat plugger penetration.

6.2.3. Materials and techniques used for obturation

Proper cleaning and shaping of the root canal system followed by complete obturation are the required goals of endodontic therapy. Ideally, obturation of the root canal system should entomb existing microorganisms that remain within infected dentinal tubules or intricate canal anatomies and escape disinfection by chemomechanical procedures. Additionally, obturation should completely seal the root canal system from reinfection from the oral cavity and from apical penetration of tissue fluids. Schilder (1967) suggested that the ideal root canal obturating material should be well adapted to the canal walls and its irregularities and that the entire length of the canal be densely compacted with a homogeneous mass of gutta-percha. Gutta-percha has been considered the “gold standard” filling material over many years in obturating root canals due to its biocompatibility, dimensional stability and adaptability to all techniques of obturation, thermoplasticity and ease of removal. Also, several sealers are used along with gutta-percha to fill anatomical variations that cannot be mechanically debrided or chemically irrigated completely. The gutta-percha fills the majority of the root canal system and acts as a carrier for the sealer, but these materials cannot be relied on to create a dependable seal (Madison and Wilcox, 1988; Oliver and Abbott, 2001; Shipper et al., 2004b). Hovland and Dumsha (1985) stated that all root canal sealers leak, but there is probably a critical level of leakage that is unacceptable for healing, which leads to endodontic failure. They also found that this leakage could occur at the interface of the sealer to dentine, sealer to gutta-percha, through the sealer itself, or by dissolution of the sealer. It has been shown by Oliver and Abbott (2001) that 99.5% of clinically placed root canal fillings did not provide an apical seal against fluid penetration and that the success of endodontic therapy is dependent on the immune response of the host to the expected apical and coronal leakage. Shipper et al. (2004b) stated that a root filling containing gutta-percha is the weak point in endodontic therapy, as also reported by Chivian (2004). To address this problem, advances in dentine bonding have led to the recent development of composite resin root filling materials.

According to the manufacturer, Resilon™ is an obturation material that was developed to replace gutta-percha and traditional sealers. In addition to meeting the requirements of an ideal root canal filling material which was delineated by Grossman (1981b), Resilon™ has a few advantages over gutta-percha. Resilon™ has been shown to be superior to gutta-percha and sealer by decreasing leakage of the root canal system, decreasing inflammation of periapical tissues, and increasing root strength (Shipper et al., 2004b; Teixeira et al., 2004b; Shipper et al., 2005). These advantages of Resilon™ appear to due to the "mono-block" adhesion created between dentine, resin sealer, and the Resilon™ core material. Also, according to the manufacturer, Resilon™ has another advantage over gutta-percha in its ability to thermoplasticize at a much lower temperature. This alleviates the concern over potential heat damage to the tooth's surrounding structures.

The lateral compaction technique (LC) involves the placement of sealer and fitted master core material, which is laterally compacted by a spreader to make room for additional accessory core materials (Ingle and West, 1994). When using this technique, it has been shown that the apical seal is best when the spreader can be placed close to the working length (Allison et al., 1981). Linear resistance in the apical area prevents apical displacement of the filling material. With better fitting master core material, penetration with a spreader close to working length is difficult without excessive force. Unfortunately, excessive force may cause root fracture. Fractures produced by spreaders have been demonstrated from 1.5 kg to 7.2 kg (Pitts et al., 1983; Holcomb et al., 1987). Clinically, useful forces have been shown to be between 1.0 and 3.0 kg (Hatton et al., 1988). Vertical load in the range of 1-3 kg have been reported as typical (Harvey et al., 1981), and adequate to deform filling material without undue risks to the tooth (Lertchirakarn et al., 1999; Dulaimi and Wali Al-Hashimi, 2005). Thus, forces associated with lateral compaction (LC) should not be a direct cause of vertical root fracture (Lertchirakarn et al., 1999). Hand spreaders encourage higher compaction forces than finger spreaders (Lertchirakarn et al., 1999), with the theoretical risk of root flexion or fracture (Tamse, 1988). For this reason, finger spreaders were used in the current study to minimize the force on the root canal during compaction and allow complete rotation of 180º without dislodgement of the filling materials.

Generally, the use of a filling core material matched to the taper of the preparation has the advantages of a uniform mass of filling core material with less sealer at the canal wall interface and within the filling mass. Unfortunately, the gutta-percha core material will not allow spreader penetration to within 1 mm of the working length (Wilson and Baumgartner, 2003). However, RealSeal™ core material may permit deeper spreader penetration without excessive force according to the manufacturer. Nielsen and Baumgartner (2006) also showed deeper spreader penetration for Resilon™ filling core material than gutta-percha core material with the same controlled pressure. Obviously, this explains why in this study the area of RealSeal™ core materials was significantly higher than the area of gutta-percha core materials at L1 and L3 using the lateral compaction technique.

Several laboratory investigations (Bal et al., 2001; Wilson and Baumgartner, 2003; Gordon et al., 2005) suggested that ISO master cone material allowed deeper spreader penetration and a larger number of accessory cone materials to be inserted, although this did not result in a superior seal against microbial leakage. Some authors recommended using non-standardized cone material after trimming to provide accurate apical sizing (Guigand et al., 2005). Other authors have encouraged using non-standardized cone material after trimming and dipping the apical 2-3 mm of the master cone in chloroform or halothane for two seconds before seating it to length in an irrigant-moistened canal to improve apical adaptation and seal of the master cone material *in vitro* (van Zyl et al., 2005).

Conventionally, all standardized filling core materials are placed in the canal with their narrow tips in an apical position. When a standardized master core material is used in the lateral compaction procedure, only a small amount of space is available in the coronal portion of the root canal to accommodate accessory filling core materials. Because every filling core has a greater diameter coronally than apically, this places restrictions on the apical placement of such cores during the lateral compaction procedure. Kersten et al. (1986), Wu and Wesselink (2001) reported that the quality of laterally compacted gutta-percha root fillings in oval root canals is poor. In the current study, the restrictions on the apical placement of accessory filling core materials probably resulted in poorer-quality root fillings in irregular apical canals than in round apical canals. This may well explain why some specimens contain low percentages of filling core materials. However, this problem is more severe when excessively tapered non-standard filling cores are used. These cores interfere with each other coronally and result in a low density of cores in the middle and apical portions of the canal (Wu et al., 2003a). Although great differences exist in canal dimensions between the largest and the smallest canals, clinically it is impossible to know the size of the canals. It has been found that the first file that binds does not necessarily measure the apical diameter (Wu et al., 2002a). Therefore, it is not always avoidable that in some cases insufficient amounts of RealSeal™ or gutta-percha are present in the apical canal, and that the apical filling contains more sealer. This may explain why many specimens gave poor results.

The quality of the adaptation of filling core materials to the wall of the apical root canal varies, and the presence of a sufficient amount of filling core materials in the apical part of the canal is essential to achieve good adaptation in canals of widely varying diameters. In both lateral compaction groups, the percentages of filling core materials were higher at L6 than at L3 and L1, indicating that regardless of which material was used, it was difficult to place accessory filling cones at the most apical levels. In the current study, for lateral compaction, the percentage of RealSeal™ sealer filled area was 11.93% at L1, whereas the percentage of AH-Plus™ filled area was 18.93% at the same level. At L3, the amount of RealSeal™ sealer occupying the root canal was 9.73%, however, for AH-Plus™ sealer it was 15.93% at the same level. For warm vertical compaction, the percentage of the RealSeal™ sealer at L1 was 12.50%, whereas the percentage for AH-Plus™ filled area was 14.47%. However, at L3 the amount of RealSeal™ sealer occupying the root canal was 7.73%, whereas for AH-Plus™ sealer it was 10.33% at the same level. In other words, it is still important to select a dimensionally stable sealer. The accessory core materials (RealSeal™ or gutta-percha) should be placed in the canal as apically as possible, after the placement of a master core material (RealSeal™ or gutta-percha). The volume of filling core materials in the canal will depend on the number and depth of the accessory filling core materials placed in the canal. If not enough core materials are placed in the canal or the accessory core materials are not placed to the proper depths, the apical part of the root filling may contain a large quantity of sealer. To facilitate the apical placement of accessory core materials, the root canal should be flared coronally and the prepared canal should have the proper taper (Buchanan, 2000). Wide coronal flaring may facilitate the apical placement of accessory core materials; however, it may significantly weaken the roots (Trope and Ray, 1992). Contrary to this belief, Kersten et al. (1986), Wu and Wesselink (2001) found that canals with increased flare resulted in significantly poorer quality of filling using the lateral compaction technique (LC). For wider and irregular-shaped canals, instead of compacting and deforming filling core materials during spreader penetration, the filling core materials were displaced laterally. This may be practically true because the compaction procedure relies mainly on the spreader.

Although in the current study, canals were obturated by a large number (eight to ten) of accessory core materials, but were still not sufficiently filled. This finding agrees with Wu et al. (2001b), who showed that quality of obturation with the cold lateral compaction technique in oval canals was less reliable; the percentage of canal area occupied by filling core materials ranged from 70% to 100%. The inconsistency may be attributed to several factors, including the irregular shape of the canal and the operator's performance of the technique. Wu et al. (2001b) reported that there was no statistically significant difference between lateral compaction and warm vertical compaction. However, the percentage of gutta-percha filled canal area was greater when using warm vertical compaction than that of cold lateral compaction in oval canals.

Generally, the L1 sections showed the lowest percentage of filling cores compared to other levels. This observation is in agreement with the findings of Eguchi et al. (1985) who showed that the apical cross-sections, 1.5 mm and 2.3 mm, from the anatomical apex, had less than 90% of gutta-percha for the lateral compaction (LC) group and the mean percentage of filling core materials improved coronally. Also, Silver et al. (1999) after performing warm vertical compaction measured the percentages of gutta-percha filled canal area in the root canals. At 6 mm from the apex, the percentage canal of filling area (PCFA) reached 97-98% using System B. However, at 2 mm from the apex, this percentage dropped to 84.5% using System B. Recently, Gordon et al. (2005) reported that the amount of gutta-percha fill in the mesio-buccal root canals of extracted upper first molars was lower (72-96%) than in the simulated canal. The lowest fill (72%) was at the 0.5 mm section level.

Voids and sealer were mostly found along the perimeter of the core materials, possibly indicating eventual loss of integrity because of poor adaptation of the filling core materials to the canal wall or may be due to spreader tracts. A better adaptation to the canal wall would reduce the width of gaps between filling core materials and the canal walls leading to a reduction in microleakage. Void formation was probably due to failure of accessory filling core materials in obturating the space created by the compacting instrument. Generally, there were no statistically significant differences in the elimination of voids for both materials when using either obturation technique except at L3. At this level, with lateral compaction, there was a significant decrease in the area of voids for RealSeal™ compared to gutta-percha probably due to spreader depth penetration. The result obtained at L3 supports the study done by Epley et al. (2006), who concluded that the two obturating techniques (lateral compaction and warm vertical “continuous wave” technique), using the new resin-based Epiphany™ obturation material, were comparable to the “continuous wave” Roth sealer technique in eliminating voids in the obturated root canal space and were significantly better than lateral compaction of gutta-percha with Roth sealer for preventing voids at the 3 mm level.

In the leakage study by Tay et al. (2005a), the weak link in Resilon-filled root canals occurred along the sealer-dentine interface unlike in gutta-percha specimens. Hiraishi et al. (2005) concluded that the low shear strength of the Resilon™ core material to the sealer compared with the composite control group suggests that the amount of dimethacrylate resin incorporated in Resilon™ may not yet be optimized for effective chemical coupling to the sealer. Likewise, Tay et al. (2006) examined the adhesive strength of the Resilon™ core material to the Resilon™ sealer using a modified microshear bonding testing design. They found that the composite control group exhibited mean shear strength 7.3 to 26.9 times higher than those of the Resilon™ groups; they also found ultrastructural evidence of phase separation of polymeric components in Resilon™. This may explain why in the current study sometimes there were gaps between the filling core materials and the sealer. Additionally, these separations may be caused by the inability of self-etching primer to reach the apical portion of the canals. Furthermore, a major problem associated with endodontic bonding is the lack of relief of shrinkage stresses created in deep, narrow canals (Davidson et al., 19901; Ferracane, 2005). Stress relief by resin flow is dependent upon cavity geometry and resin film thickness (Feilzer et al., 1989; Alster et al., 1997). In a Class I box-like cavity, there is five times more bonded surface area than unbonded surface area. The ratio of the bonded to the unbonded surface area is called the configuration factor or C-factor. During polymerization, the unbonded surface can move and flow, thereby relieving shrinkage stresses. However, as the unbonded surface area becomes small, as in a long narrow root canal, there is insufficient stress relief by flow and a high probability than one or more bonded areas will pull off or debond. Bouillaguet et al. (2003) also reported that root canals have high cavity configuration factor (C-factor) that contribute to polymerization stresses created by resin-based materials along root canal wall. Polymerization shrinkage of the Resilon™ sealer was suggested as the possible cause of gap formation leading to apical leakage when using Resilon™ as reported by Tay et al. (2005a).

The "continuous wave of condensation" technique developed by Dr. L. Stephen Buchanan, serves as a hybrid of the cold lateral and warm vertical compaction and it has shown much promise in three-dimensional filling of the root canal system (Buchanan, 1994). The System B was set at 150°C for RealSeal™ following manufacturer recommendations. It is possible that a higher heat source temperature may increase the RealSeal™ temperature closer to gutta-percha; however, a significant increase may cause damage to the physical structure of Resilon™ as reported by the manufacturer or damage to the periodontal ligament (Eriksson and Albrektsson, 1983).

Factors that may influence the poor performance of the System B technique are:

1. Anatomical variability of teeth used like size and shape of the root canal.
2. Selection of filling core materials.
3. Selection of the plugger size, and its proximity to the apex.
4. Heating conditions including the depth of heat application, heating time and temperature.

Buchanan (1996) suggested that pluggers should penetrate 5-7 mm less than working length. Nevertheless, some authors investigated the influence of the heat penetration depth (Wu et al., 2002b) and canal width (Wu et al., 2000d; Wu et al., 2002b) on the adaptation of gutta-percha to the canal walls. When using different heat sources for warm vertical compaction techniques, better results were found by increasing the depth of heat application due to the increased softening of the gutta-percha which in turn duplicates canal irregularities (Smith et al., 2000; Wu et al., 2002b; Young Jung et al., 2003). Nevertheless, when the plugger was inserted to 3-4 mm from the working length, it was still found that some cross-sections of warm vertical compacted root fillings cut at 1 mm from the obturated terminus appeared to be similar to those of a single filling core material, that was encased in a thick layer of sealer. This indicated that the filling core material at this level had not been heated before the vertical compaction. This observation is consistent with Wu et al. (2001b) who experimented with the “continuous wave of condensation” technique. He and his colleagues found that the apical gutta-percha ratio was low in some specimens and the sealer thickness was high. The insufficient softening of the filling core material by heat was thought to be responsible for low filling core adaptation. In some studies (Hall et al., 1996; Wu et al., 2000c) the sealer percentages (42-63%) were higher than reported in the present study. Of course, the outcome of the filling procedures used depends on the application power, amount of sealer and its physical properties of flow and film thickness (Wu et al., 1997; Wu et al., 2000c).

In this study, voids occurred primarily between the canal wall and the root filling. They were also present within the filling mass, generally at levels associated with the segmental backfilling of the canal. Inadequate compaction pressure resulting from inadequate hydraulic forces stemming from the use of a plugger is a reason for the occurrence of voids in both filling core materials. The relative increase in the percentages of voids occupying the canals at L3, the level of the secondary filling materials, when compared to L6, would suggest that the root filling may be prone to leakage in the critical apical third of the canal, particularly after sealer shrinkage and dissolution.

Resin filling material in two L1 sections stripped out of the canal during sectioning which may have been due to over preparation of the canals leaving very little dentine structure to support the filling core material when sectioned, or inadequate bonding of sealer and filling core material to the dentinal wall.

The oval canal shape may make it difficult to clean and fill (Wu et al., 2001b; Wu and Wesselink, 2001). Kersten et al. (1986) reported that both lateral compaction as well as vertical compaction have been widely used in endodontic treatment, although their quality may differ in canals with different shapes. In their study, Wu and Wesselink (2001) reported a high percentage of oval canals in the apical portion of human roots (≥50%) with the diameter of these oval canals tending to decrease apically. The long diameter of oval canals was found to decrease apically (Wu et al., 2000d); that is, the canal shapes changed toward round. Cold lateral compaction may produce better fillings in round canals than in long oval canals (Wu et al., 2001b), and this probably explains why there were no significant differences recorded for both techniques at L1. There were no significant differences in obturation quality between warm vertical “continuous wave” techniques and lateral compaction techniques at L1 which concurred with other investigations that showed no significant difference in apical dye leakage between the two groups (ElDeeb et al., 1985; Evans and Simon, 1986).

Both irregular canal shapes and inadequate biomechanical preparations may negatively influence filling quality. Wu et al. (2001b) postulated that irregularly shaped canals may be filled more effectively by warm vertical compaction techniques, provided they are clean. Although in this study some short recesses were obturated by cold lateral compaction, some long and narrow recesses that were obturated by the warm vertical compaction, tended not to be completely obturated by cold lateral compaction. These findings are consistent with those of Wu and Wesselink (2001). In their study, 62% of the recesses in oval canals were unfilled or incompletely filled by the cold lateral compaction technique. In the current study, areas beyond the reach of the mechanical action of endodontic instruments in canals with irregular shapes frequently remained unfilled when the lateral compaction and warm vertical compaction techniques were used. These findings are in agreement with Wu et al. (2001a), who used root canals of mandibular incisors, which were obturated using the warm vertical compaction technique and backfilled with injectable thermoplasticized gutta-percha. Cross-sections of the roots showed that warm gutta-percha could not fill the canal area where debris remained after instrumentation.

Oval shaped and larger diameter root canals would require excessive preparation for lateral compaction to be effective. However, the use of a warm compaction technique using matched-taper core material would ensure adequate adaptation to canal irregularities. Therefore, the quality of the cold compaction technique and warm compaction in oval canals may be an indication of their applicability in irregularly shaped canals. In the current study, the warm compaction technique for both materials produced higher percentages of filling core materials than the cold lateral compaction technique at 3 mm and 6 mm from the obturation terminus. In other words, the obturation quality improved at L3 and L6, where sealer and voids were rarely seen, especially at L6. Sealer had probably been pushed away during compaction of the thermosoftened filling core materials and this corroborates with Wu et al. (2000c), who reported that sealer may be removed from the canal wall by the obturation procedure regardless of the sealer placement methods.

6.2.4. Scanning electron microscopy

The sealing capability of RealSeal™ may be attributed to the "mono-block" which is created by the RealSeal™ core material closely adapting to the RealSeal™ sealer. This sealer, in turn, adheres to the dentine walls because of the use of primer before RealSeal™ sealer. This primer prepares the root canal surface through an etching process that creates finger-like dentinal projection. This allows for a lock and key type bond between the root canal, sealer and core material (Aptekar and Ginnan, 2006). In this study, fissures and gaps were observed between gutta-percha and the dentine, which may be due to the gutta-percha being pulled away from AH-Plus™ and also AH-Plus™ pulled away from dentinal tubules. That in turn creates a gap between the gutta-percha and AH-Plus™ and/or between AH-Plus™ and dentine for harmful bacteria to multiply and create an avenue for microleakage. This may explain the high percentage of voids in gutta-percha groups than in RealSeal™ groups. The scanning electron microscopy results here are in line with those of others which mentioned that Resilon™ filling material produced better seal than gutta-percha and traditional sealers (Shipper et al., 2004b; Chivian, 2004; Aptekar and Ginnan, 2006).

6.3. Limitations of this study

1. One of the most difficult parameters to control in this study was the extent of anatomical variations that are generally present in human teeth.
   (More than 150 extracted single-rooted mandibular premolars were examined to obtain the study sample).
2. This *in vitro* study attempted to represent root canal obturation concepts that can be applied to a clinical setting, however, results may vary in *in vivo* conditions.
3. There was difficulty in standardizing the amount of sealer applied to the apical portion of the canal.
4. There was difficulty in applying the self-etching primer to coat the entire wall of the canal.