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The Effect of Mechanical Vibration (Acceledent, 30Hz) applied to the hemi-maxilla on Root Resorption Associated with Orthodontic Force

A Micro-CT Study

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Discipline of Orthodontics

Faculty of Dentistry

University of Sydney

Australia

A thesis submitted in partial fulfilment of the requirements for the Doctor of Clinical Dentistry in Orthodontics
Dedication

To my loving wife, Sabina for all of your patience, support and encouragement.

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The effect of mechanical vibration (Acceledent) on root resorption and tooth movement after application of orthodontic force. A micro−CT study.

Daniel Tan

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The effect of mechanical vibration (Acceledent) on root resorption and tooth movement after application of orthodontic force. A micro-CT study.

Daniel Tan

Declaration

CANDIDATE CERTIFICATION

This is to certify that the candidate carried out the work in this thesis in the Orthodontic Department at the University of Sydney, and this work has not been submitted to any other university or institution for a higher degree.

Daniel Tan
The effect of mechanical vibration (Acceledent) on root resorption and tooth movement after application of orthodontic force. A micro-CT study.

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**Abbreviations**

<table>
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<th>Description</th>
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<tr>
<td>2D</td>
<td>Two dimensional</td>
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<tr>
<td>3D</td>
<td>Three dimensional</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>BMP</td>
<td>Bitmap</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>EARR</td>
<td>External Apical Root Resorption</td>
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<tr>
<td>g</td>
<td>Grams</td>
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<tr>
<td>H&amp;E</td>
<td>Haematoxylin and Eosin</td>
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<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IL-1</td>
<td>Interleukin-1</td>
</tr>
<tr>
<td>IL-1β</td>
<td>Interleukin – 1 beta</td>
</tr>
<tr>
<td>ISO</td>
<td>International organisation for standardisation</td>
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<td>LM</td>
<td>Light Microscopy</td>
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<tr>
<td>mm</td>
<td>Millimetres</td>
</tr>
<tr>
<td>μm</td>
<td>Micrometer</td>
</tr>
<tr>
<td>Nd-Fe-B</td>
<td>Neodymium</td>
</tr>
<tr>
<td>PEMF</td>
<td>Pulsed Electromagnetic Field</td>
</tr>
<tr>
<td>TIFF</td>
<td>Tagged Image File Format</td>
</tr>
<tr>
<td>TA</td>
<td>Thermoplastic aligner</td>
</tr>
<tr>
<td>RANKL</td>
<td>Receptor activation of nuclear factor kappa β ligand</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission electron microscopy</td>
</tr>
<tr>
<td>TRAP</td>
<td>Tartrate resistant acid phosphate</td>
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1 Introduction

Root resorption is the destructive process of the cementum and/or dentine layers of a tooth root due to clastic cell activity which leads to a subsequent loss root structure of a tooth. This process may be physiological or pathological. Physiological root resorption of deciduous teeth naturally occurs when the permanent teeth begin to erupt. It may also occur to a small degree in the permanent dentition associated with physiological tooth movement.¹ Pathological root resorption has been related to orthodontic tooth movement, trauma, and ectopic eruption of adjacent teeth and in association with other pathology.

Bates² was the first to describe root resorption of permanent teeth in 1856. The link between orthodontics and root resorption was identified in 1914 by Ottolengui. The term “Orthodontically induced root resorption (OIIRR)” was introduced by Brezniak and Wasserstein to describe the type of root resorption experienced during orthodontic treatment.³ It is a pathological surface or transient inflammatory root resorption that occurs due to the presence of an orthodontic force on a tooth. It is accepted that most individuals will experience some degree of root shortening after orthodontic treatment. Fortunately the presence of severe root shortening is relatively uncommon after orthodontic treatment⁴.

The exact aetiological factors of OIIRR are still unclear. These factors can be either patient biological related or treatment mechanics related⁵. Biological factors described in the literature include genetic factors, dental age, root morphology, bone density and a previous history of root resorption. Treatment mechanic factors that have been suggested to cause an increase in root resorption are force magnitude, duration of treatment, the amount of tooth movement, direction of tooth movement, the type of bone.
Vibration in orthodontics has been applied with the main aim of increasing the rate of orthodontic tooth movement by accelerating the periodontal and bony tissue modelling and remodelling processes. This has the benefit of decreasing the duration that a patient has fixed appliances on their teeth. In the literature, increased treatment duration has been associated with an increased risk of caries\(^6\), periodontal problems\(^7\) as well as a higher risk of root resorption\(^8\)-\(^10\).

Vibration has the advantage of minimal side effects in comparison to other methods of accelerating tooth movement such as local or systemic medicines and has proven to be a safe low impact alternative that enhances bone remodelling in the medical field.

A new device called Acceledent has been introduced to the market and aims to achieve an increased rate of tooth movement by enhancing bone remodelling using pulsating forces. Invented by Dr Jeremy Mao, it is intended to be used by a patient in conjunction with fixed orthodontic appliances or removable sequential aligner treatment for 20 mins per day. It vibrates at a frequency of 30Hz and has force amplitude of 20 grams.

Although vibration in conjunction with orthodontics may accelerate bone and periodontal tissue remodelling, there is very limited research on the effect of this accelerated remodelling on the root surface of teeth.

The aim of this study is to compare the root resorption that occurs on human upper first premolar teeth following the application of a buccally directed force (150g) with and without vibration from Acceledent. The experimental teeth were extracted after four weeks of force application and examined using Micro-computed tomography. This method has been shown to be more accurate and reliable at quantitative measurements than previous studies using two dimensional radiographs, light microscopy and scanning electron microscopy and transmission electron microscopy\(^{11\text{-}14}\).

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2 Literature review

2.1 Cementum

The tissues that support a tooth consist of the gingiva, cementum, periodontal ligament and alveolar bone. Tooth Cementum, first described in 1853\textsuperscript{15}, is a mineralised tissue formed by cementoblast cells on the entire surface of root dentine. It is derived from dental follicular connective tissue that forms subsequent to Hertwig’s root sheath disintegration.\textsuperscript{16}

Cementum has been classified into five different subtypes based on the presence (cellular) or absence (acellular) of cells and the source of collagen (extrinsic vs. intrinsic).\textsuperscript{17} Although cementum has many similarities with bone, it contains considerably higher fluorine content, is non-innervated and avascular and generally exhibits little or no remodelling. It contains approximately 45% mineralised inorganic material (hydroxyapatite crystals), 33% organic material and 22% water. Cementum increases in thickness from 20-50µm at the cementoenamel junction to approximately 150-200µm towards the root apex\textsuperscript{18}. Cellular cementum also continues to increase in thickness throughout life.

The major role of cementum is to provide anchorage of the tooth in its alveolus. Acellular cementum serves to anchor the periodontal ligament fibre bundles to the tooth while cellular cementum has an adaptive and reparative role. Another function of the cementum is to assist in maintaining occlusal relationships\textsuperscript{19}. With increasing wear of the occlusal and incisal surfaces of the teeth, compensatory eruption of the tooth and cementum deposition occurs. The deposition of new cementum is thought to maintain the width of periodontal ligament space at the root apex. Although cementum is deposited throughout life, there does not appear to be any predictable correlation between functional forces and the thickness of cementum.\textsuperscript{19}

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Orthodontic tooth movement is possible because of the greater resistance of cementum than bone to resorption.20 The high rate of turnover of bone results in tissue that is newer and more immature than the adjacent cementum. Thus the cementum is surrounded by older and more mature collagen which is more resistant to chemical changes than the bone.21

2.2 Orthodontic tooth movement and OIIR

Orthodontic Tooth movement is made possible by remodelling changes that occur in the dental and paradental tissues including the dental pulp, periodontal ligament (PDL), alveolar bone and the gingiva22. Research by Sandstedt, Oppenheim23 and Schwarz24 has lead to the classic pressure-tension theory of orthodontic tooth movement. It occurs when forces applied to a tooth creates areas of compression and tension within the PDL25 which alters the blood flow. A change in the PDL’s vascularity results in local synthesis and release of key molecules such as inflammatory mediators. This induces an acute inflammatory response which is necessary for tissue deposition on the tension side and resorption on the pressure side.

Bone resorption is crucial to orthodontic tooth movement by removing alveolar bone from the path of the moving tooth root.22

With light forces on a tooth and associated maintenance of vascular patency, clastic cells adjacent to the lamina dura start to remove bone in the process of direct (or frontal) resorption. Tooth movement begins soon after.26

Indirect (or undermining) resorption is associated with heavy forces which occlude the blood vessels and cut off blood supply to areas within the PDL. A sterile necrosis called the hyalinization zone develops. When this occurs, remodelling of bone bordering the necrotic area of the PDL must be performed by osteoclasts which attack the underside of the bone immediately adjacent to the
necrotic tissues. Undermining resorption is associated with a delay in tooth movement as well as pain for the patient.26-27

It is desirable to achieve orthodontic tooth movement with as much frontal resorption as possible as it is more efficient. However, in practice, even light forces have been associated with areas of hyalinisation and direct and indirect resorption appear concurrently.28

During the resorption of bone process, clastic cells may also attack the outer cementum layers of the tooth root. If there was no difference between bone and cementum, orthodontic tooth movement would cause them to resorb equally. Although bone and cementum have many similarities, they behave very differently. Cementum is more resistant to resorption than bone which results in preferential bone resorption and orthodontic tooth movement.20,29

If the reparative capacity of cementum is exceeded by root resorption, it will present as the permanent loss of root structure.30

### 2.3 Classification of root resorption

Andreasen31 defined three types of external root resorption:

1. **Surface resorption** – involves small outlining areas followed by spontaneous repair from adjacent intact parts of the periodontal ligament. This is a self limiting process.

2. **Inflammatory resorption** – initial root resorption has reached dentinal tubules of an infected necrotic pulpal tissue.

3. **Replacement resorption** - bone replaces the resorbed tooth material and then leads to ankylosis
Tronstad in 1988 classified root resorption into inflammatory or replacement resorption. Inflammatory resorption occurs in the presence of denuded cemental areas which are colonised by multinucleated cells. Inflammatory resorption can be either transient or progressive. Transient inflammatory resorption is usually undetectable on radiographs and occurs when damaging stimulation is minimal or for a limited time. Resorption is repaired by cementum like tissue.

If the damaging stimulation is for a longer period of time, progressive inflammatory resorption will occur. This can be observed radiographically.

Replacement resorption occurs when extensive necrosis of PDL leads to bone formation onto a denuded area of the root surface (ankylosis). As the tooth becomes part of the bone, remodelling will eventually lead to destruction of the tooth by the bone.

Root resorption occurring from orthodontic treatment is either a surface resorption or transient inflammatory resorption. Replacement resorption is not normally seen after orthodontic treatment.

Brezniak and Wasserstein suggested the term orthodontically induced inflammatory root resorption (OIIR) to distinguish this type of resorption from others such as those caused by trauma, periapical lesions of periodontal disease. They then described three degrees of severity:

1. Cemental or surface resorption with remodelling – only the cemental layers are resorbed and then fully regenerated.

2. Dentinal resorption with repair – cemental and the outer layers of dentine are resorbed and usually repaired with cementum material. This process may alter the shape of the root from its original form.
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3. Circumferential apical root resorption – full resorption of all hard tissues of the root apex occurs. This leads to irreversible root shortening. External surface repair and remodelling of sharp edges occurs in the cemental layer.

2.4 Orthodontically induced root resorption

Root resorption is commonly seen on dental radiographs as the permanent shortening of the tooth root. Normally, the cementum layer of a tooth root does not undergo appreciable resorption. However, with orthodontic force application on a tooth, sometimes excessive resorption of root cementum and dentine is induced which will eventually lead to the irreversible shortening of a tooth root’s length.

Root resorption in orthodontics has been referred to by many terms in the literature such as apical root resorption, external apical root resorption (EARR) or orthodontically induced inflammatory root resorption (OIIRR). It has long been recognised in the field of dentistry, especially in orthodontics. Over a century ago in 1856, Bates discussed root resorption in permanent teeth as a result of trauma. Ottolengui, in 1914 was able to relate root resorption specifically to orthodontic treatment. However, it was in 1927, when Ketcham demonstrated root resorption with radiographic evidence after orthodontic treatment, that root resorption began to become a great concern.

At this time, the terms absorption and resorption were used interchangeably to describe the loss of apical root. This issue was put to rest by an article written by Becks and Marshall in 1932.

Becks and Marshall preferred the resorption over absorption as tissues constituting a tooth such as calcium or phosphorous are first absorbed by the blood from the food and then deposited as a
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tooth. Occasionally the calcium and phosphorous in a tooth are “absorbed again” from the root by the blood. The term “resorb” means, by its derivation, “absorb again”\(^\text{37}\). They initially defined root resorption as the destruction of formed tooth structure.

More recently, root resorption has been defined as the active removal of mineralised cementum and dentine.\(^\text{38}\)

To describe root resorption that specifically occurs in association with orthodontic treatment, Bresniak and Wasserstein suggested the term orthodontically induced inflammatory root resorption.\(^\text{3}\)

However, even when no radiographic signs of root resorption can be visible, it is accepted that most teeth undergoing orthodontic tooth movement will experience some degree of root resorption followed by repair.\(^\text{39}\) The clinical significance of root resorption will depend on individual susceptibility and biological reaction to orthodontic treatment.

2.4.1 Mechanism of root resorption

Root resorption as a result of orthodontic tooth movement is associated with a local over compression of the periodontal ligament with the development of a sterile necrosis (hyalinised zone). Historically, Swartz\(^\text{40}\) hypothesised that the ideal force to move a tooth would be those which just overcome capillary blood pressure (20-26 grams per square centimetre). If the force placed on a tooth exceeded the capillary blood pressure, the capillary would collapse, cut off blood circulation and lead to areas of tissue necrosis and thus root resorption. It is thought that when resorption processes exceed the reparative capacity of cementum, OIRR will ensure.\(^\text{41}\)
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Much of what we know about the cellular processes involved is from mice and rat studies. Brudvik and Rygh\textsuperscript{38,42-46} in a series of resorption studies found OIIR is part of the hyaline zone elimination process and follows a consistent pattern.

OIIR starts in the circumference of the main necrotic hyalinised tissue and continues a few days later with the removal of the main hyalinised zone.\textsuperscript{42}

Two different cell populations are involved in the root resorption process.

Cells involved in the initial phase of resorption (1-3 days) are not odontoclasts as they lack tartrate resistant acid phosphatase (TRAP) enzyme. They are macrophage –like cells whose role is to eliminate the necrotic tissues.\textsuperscript{47}

During removal of the hyaline zone, the nearby cementoid layer can be damaged, exposing the underlying cementum. Rygh\textsuperscript{21} suggested the cementoid layer acts as defence against resorption describing it as a resorption-resistant “coating”. Reitan\textsuperscript{48} confirmed this by demonstrating that the presence of a cementoid or predentine layer on the root delays the resorption process.

The initial phase of cells are followed by multinucleated (odontoclasts) as well as mononucleated TRAP positive cells which invade into the hyalinised tissue from the periodontal membrane as well as the adjacent alveolar bone. They attack the cementum and eventually dentine.\textsuperscript{43} According to Shaza and Hartsfield\textsuperscript{30}, Kvam\textsuperscript{49} was the first to describe resorption lacunae penetrating the cementum into dentin in human premolar teeth.

The root surface under the main hyaline zone resorbs several days later. This resorption process continues at the same time repair processes in the periphery are taking place. It stops when no hyaline tissue is remaining and/or the force level decrease.
2.4.2 Repair processes

Repair of root resorption craters begins when the force applied is discontinued or reduced below a certain level. This has been recorded to begin as early as the first week of retention. The reparative process increases with time and especially during the first 4 weeks of retention. However, by the 5th and 6th weeks, repair seems to slow and reach a steady state.

Brudvik and Rygh described the process of repair beginning from the periphery in the resorbed lacunae where the PDL has been re-established while active resorption still occurs beneath the main, more centrally located over compressed hyalinised zone.

After 10 days of tooth movement multinucleated resorptive cells and collagen producing fibroblast-like cells occupy the same resorption lacuna. The fibroblasts invade the lacunae from the circumference indicating a transition of resorption to repair.

Approximately two weeks after force is removed, different phases of repair can be observed with the placement of new cementum or coverage of root dentine with fibrillar structures.

By three weeks, mineralised cementum fills the resorption lacunae and PDL attachment is restored. Light Microscopy (LM) studies also demonstrate that repair of resorption lacunae can occur in the presence of active force at the peripheries of the resorbed areas.

In contrast, to this, Barber and Sims found repair to proceed from the centre of the resorption cavity and moving outwards. Owman-Moll and Kurol also found early repair initially began only on the bottom of the resorption cavities with occasional reparative cementum extending onto the lateral walls. No reparative cementum was found on the lateral walls alone. The repair process of root resorption was achieved mainly by deposition of cellular cementum with acellular cementum only at the initial phase of healing.
Both repair patterns from the periphery and the centre were observed by Sismanidou and Lindskog in adolescents. They also found that onset of reparative cementum appeared after 2 weeks of force discontinuation and initially only involved acellular cementum formation. Gradually this changed to cellular cementum at the more advance stages of healing.

### 2.5 Incidence and prevalence of root resorption

#### 2.5.1 Untreated populations

Root resorption is a necessary natural process for deciduous teeth during the eruption of their permanent successors. Permanent teeth also undergo a certain amount of apical root resorption. This may be a normal physiological process similar to continuous bone remodelling.

Root resorption of teeth has been reported in both orthodontically treated subjects as well as in untreated populations, however, orthodontically treated patients are more likely to have severe shortening of the root.

Henry and Weinman used a histological study of 261 non orthodontically treated teeth and found 90.5% displayed evidence of root resorption. Root resorption seemed to affect the apical region the most followed by the mesial, buccal, distal and lingual surfaces. They also reported that resorption increased with increasing age.
2.6 Orthodontically treated populations

The incidence of orthodontically induced root resorption varies widely in the literature. This can be explained by the various study methodologies, which historically, has looked at root resorption either by histological sectioning or radiographic images.

Diagnosis can be by panoramic or periapical radiographs. Clinical diagnostic radiographic studies generally report a lower incidence than histological studies.

Ketcham\textsuperscript{35} was the first to show radiographic evidence of root resorption after orthodontic treatment. While 1% of the untreated population had some root resorption, he found 21% of five hundred patients had evidence of root resorption. In contrast, Rudolph in 1940 found treated teeth displaying root resorption had an incidence of 75% and 100% compared to a non-treated sample which had an incidence of 5%\textsuperscript{59,60}

Massler and Malone also reported relatively high numbers with 86.7% of non-treated patients and more than 90% of treated patients presenting with signs of root resorption.\textsuperscript{61}

Levander and Malmgren studied the root resorption pattern of 610 upper incisors after treatment with either an edgewise or Begg technique. They found only 1% of teeth had severe root resorption and that this was related to minor resorption after the initial 6-9 months of treatment.

Sameshima and Sinclair in 2001 using full mouth periapical films reported that greater than 2 mm of OIIR was seen in 25% of the 868 treated patients. Killany reported a similar frequency of 30% with OIIR greater than 3 mm. Only 5% of treated patients were found to have >5 mm of root resorption\textsuperscript{57}.

With panoramic or periapical radiographs, apical root resorption is usually less than 2.5 mm and varies from 6% to 13% for different teeth\textsuperscript{4}. 
Histology of orthodontically moved teeth in animal and human studies tends to report a greater incidence of OIRR ranging from 0 to 100%.

An early histological report by Henry and Weinmann found 90.5% of untreated teeth showed areas of resorption, most of which occurred at the root apex. They concluded that it is normal for a tooth to incur some degree of resorption during its life.

In most cases, the amount of OIRR experienced is considered minimal and not clinically significant. If this is the case, it can be classified as minor or moderate. This is approximately 2mm from the apex of the maxillary central incisor, with loss on the lateral incisor being somewhat greater. Severe resorption is defined as loss of root structure exceeding 4mm, or a third of the original root length. Fortunately this is only seen in 1%-5% of teeth.
2.7 Aetiology and risk factors associated with OIIR

Although many risk factors have been found, our predictive power in assessing the possibility of future resorption is still poor. Individual variation in biologic response to orthodontic forces and genetic predisposition may explain the variation in OIIR that occurs. Brezniak and Wasserstein in their review of the literature divided risk factors into biological and mechanical factors.

2.7.1 Biologic factors

2.7.1.1 Genetic factors

OIIR tends to have a strong genetic component. Although no definite genetic conclusion has been found, autosomal dominant, autosomal recessive and polygenic modes of inheritance are possible.\textsuperscript{5,62}

Harris et al\textsuperscript{63} used a sib-pair model to examine the genetic influence of EARR. They reported that genetic predisposition to EARR had high heritability ($h^2 = 70\%$).

Recently, polymorphism of the pro-inflammatory cytokine Interleukin-1 (IL-1) gene cluster has been associated with the severity of adult periodontitis and increased tissue resorption\textsuperscript{64}. IL-1\textbeta has been implicated in bone resorption during orthodontic tooth movement. Humans and animals undergoing orthodontic tooth movement have been reported to have increased levels of IL-1\textbeta in their gingival tissues and gingival crevicular fluid\textsuperscript{65-68}. The speed of tooth movement is also related to IL-1 gene cluster polymorphisms.\textsuperscript{69-70}
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Al-Qawasmi et al\textsuperscript{71-72} investigated the clinical screening of orthodontic patients for IL-1\(\beta\) genotype by analysing DNA from a cheek swab. Their analysis indicated that IL-1\(\beta\) polymorphism accounted for 15\% of the total variation of maxillary incisor OIIR and patients homozygous for the IL-1\(\beta\) allele 1 had a 5.6 times increased risk of OIIR greater than 2mm compared to those that did not. These findings suggest that genetics are just one factor that contributes to the complex aetiology of OIIR.

OIIRR of the maxillary central incisors have the highest heritability component and are usually the most severely affected.\textsuperscript{63,73}

The possibility of genetic testing and screening for patient susceptibility to OIIRR may become a reality in the future. However, presently, if a child has had previous orthodontic treatment, viewing of their post treatment radiographs may prove invaluable to the treatment of subsequent siblings.\textsuperscript{74}

\textbf{2.7.1.2 Race}

Sameshima et al in their sample of 868 patients reported that Asian patients were found to experience significantly less root resorption than white or Hispanic patients. In contrast, Smale et al\textsuperscript{75} recruited patients from 3 different centres in 3 countries and found no differences in resorption among the subsamples. They reported that this justified their decision to combine all patients into one group for analysis.

\textbf{2.7.1.3 Systemic factors}

It has been proposed that systemic factors such as the inflammatory mediators produced outside of the PDL may act to enhance cellular interactions involved in root resorption\textsuperscript{76}. 

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Davidovitch et al applied an orthodontic force on the maxillary molars of guinea pigs. These guinea pigs were induced with allergic asthma. It was noted that the numbers of alveolar bone osteoclasts increased in the compressed PDL areas over control guinea pigs which suggested that cell populations involved in resorption were influenced by inflammatory mediators produced by asthma.⁷⁶

Patients with treated as well as untreated chronic asthma have been reported to have an increased incidence of OIIRR compared with healthy individuals.

McNab et al⁷⁷ used panoramic films to measure the root resorption on posterior teeth of asthmatics and healthy patients after fixed appliance treatment. Asthmatics had significantly more external apical root resorption of posterior teeth compared with the healthy group (P = .0194). Although increased incidence of OIIRR was reported, both asthmatics and healthy patients had similar amounts of moderate and severe resorption.

Using the hypothesis that inflammatory mediators enhance root resorption, it was theorised that OIIRR of the upper first molars in asthmatics may be the result from local sinus inflammation.

It was concluded that although the incidence of OIIRR may be increased in asthmatics, it only tends to be in the form of increase in root blunting. Therefore asthmatics are only at a minimal risk of posterior OIIRR that may not adversely affect the function or longevity of these teeth.

Similar findings were reported in a group of 60 Japanese orthodontic patients. Pre-treatment records revealed that the incidence of allergy and root morphology abnormality was significantly higher in the root resorption group. Also the incidence of asthma tended to be higher in the root resorption group. The authors concluded that allergy, asthma and abnormal root morphology may be high risk factors for excessive OIIRR in Japanese patients.⁷⁸
Owman-moll and Kurol in 2000 analysed factors that might be associated with OIIRR by examining extracted maxillary premolars of 96 adolescents after buccal movement. A preliminary screening of possible risk factors such as root morphology, allergy, nail biting, medication etc was performed. Interestingly, only those subjects with allergies showed an increase risk of root resorption, however, this result was not statistically significant.

### 2.7.1.4 Nutrition

Nutrition was suspected to be linked to root resorption in the past. Calcium and vitamin D deficiency in animals have been reported to have root resorption\(^7\). Brezniak and Wasserstein\(^5\), in their review of the literature reported that nutritional imbalance is not likely to be a major factor in root resorption.

### 2.7.1.5 Dental age

Orthodontic treatment does not stop root development. The stage of root formation at the onset of treatment has been discussed in terms of lessening the severity of OIIR. There are some studies which suggest that incompletely formed roots exhibit less root resorption than in patients treated when root formation is complete.\(^8\) Although they may have less OIIRR, early orthodontic tooth movement may also prevent the roots from reaching their “normal” length.\(^9\) Although this has been reported, these teeth reach a significantly greater length than those that were fully developed at the start of treatment\(^10\).
Rosenberg reported that orthodontic treatment increased the dilacerations incidence of roots from 25% to 33% after treatment. This was found to be higher in canines than premolars.\textsuperscript{83}

Brezniak and Wasserstein\textsuperscript{5} reported in their review of the literature that orthodontic treatment should begin as early as possible since there is less root resorption in developing roots and young patients show better muscular adaptation to occlusal changes.

\subsection*{2.7.1.6 Chronological age}

With increasing age, the periodontal membrane becomes less vascular, aplastic, and narrow, the bone more dense, avascular, and aplastic, and the cementum wider. Reitan\textsuperscript{25} suggested that these age changes may explain why adults have a higher susceptibility to root resorption.

However, most studies have found that chronological age and OIIR to be poorly correlated and that chronological age may not be a significant factor in the occurrence of OIIR\textsuperscript{74}.

Sameshima and Sinclair\textsuperscript{8} reported that root resorption of the mandibular incisor and canine regions is more in adults than in children; however age was not found to be a statistically significant factor in the maxillary anterior region.

\subsection*{2.7.1.7 Gender}

There are conflicting reports in the literature regarding gender susceptibility to OIIRR. Some reports suggest there to be no difference in the incidence of OIIR and gender.\textsuperscript{8-9,63,84-85}
The effect of mechanical vibration (Acceledent) on root resorption and tooth movement after application of orthodontic force. A micro-CT study.

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Others claim that girls are more susceptible than boys.\textsuperscript{62,86} Newman\textsuperscript{62} found females to be more prone to root resorption than males with the sex ratio of their sample to be 3.7 females to 1 male. However, this ratio may partially be explained by the fact that orthodontists probably saw a higher frequency of female patients that were included in the study.

In comparison, studies by Baumrind et al\textsuperscript{87}, Remington et al\textsuperscript{88} and spurrier et al\textsuperscript{89} have reported a higher incidence and severity of OIIRR in males when compared to females.

\subsection*{2.7.2 Habits}

Nail biting and tongue thrust habits have been implicated in causing more severe root resorption.\textsuperscript{62,90}

Harris and Butler looked at adolescents with open bites and found the roots of permanent maxillary incisors were significantly shorter than matched deep bite subjects. They explained that tongue thrusting in association with an anterior open bite produced intrusion and torquing forces on the incisors. This might explain why roots of the upper anterior teeth were already compromised before mechanotherapy.\textsuperscript{91}

\subsection*{2.7.2.1 Root morphology}

Most studies have found teeth with abnormally shaped roots have a greater risk of OIIR than teeth with normally shaped roots. Sameshima and Sinclair in a study of 868 cases found the worst resorption to be on the maxillary lateral incisors and in teeth with pipette, pointed or dilacerated roots.\textsuperscript{8}
Long roots, narrow roots and deviated root shape have been identified as significant risk factors. Kjaer found strong associations between root morphology such as invagination, length of root, taurodontism, and root shapes and increased root resorption.

Brin et al in their study found teeth with unusual morphological roots before treatment were only slightly more likely to have moderate to severe OIIR when compared to teeth with normal roots. However, they said that this could not be a significant predictor of OIIR.

### 2.7.2.2 Previous trauma and endodontically treated teeth

Dental trauma and orthodontic treatment after dental trauma is generally considered a predisposing factor for OIIR. Linge and Linge investigated the incidence and extent of apical root resorption in maxillary incisors in 719 consecutively treated patients. Of this sample, 110 patients reported trauma to the incisors prior to treatment. The trauma group had more root resorption in terms of average root length reduction as well as for the most severely affected incisor when compared to the rest of the sample. This difference was found to be highly significant (p<0.001). The authors recommended screening patients prior to treatment with records of previous incisor trauma.

In contrast, other studies such as Brin et al, Kjaer and Mandall et al found no difference in the incidence of OIIR when comparing teeth that had previous trauma and those that had not. Levander et al also found no statistical significant correlation between trauma history and OIIRR.

The correlation between endodontic treatment and OIIRR is not yet conclusive. This may be due to some bias in the study design which has included teeth that have a history of trauma. Steadman’s review in 1942 suggested that roots of the root canal tooth may act as a foreign body and “melt
away as the years pass. Wickwire et al. reported that orthodontic movement of endodontically treated teeth exhibited a greater frequency of root resorption than their vital controls.

Other authors have reported no significant differences in the amounts of root resorption experienced in vital and endodontically treated teeth.

Spurrier et al. compared the severity of apical root resorption in endodontically treated incisors and the contralateral vital tooth as a control. Forty three patients were examined. Surprisingly vital incisors resorbed to a significantly greater degree than endodontically treated incisors with a mean difference of 0.77mm. They reported that although it was significant, this difference would be virtually undetectable at the clinical level.

Mirabella et al.'s results agreed that endodontically treated teeth resorb significantly less than their contralateral controls.

2.7.2.3 Type of malocclusion

Many believe that the presence of an overjet is a strong predictor for OIRR due to large distances the anterior teeth have to move for overjet correction.

Increased overjet but not overbite has been significantly associated with greater root resorption.

The type of malocclusion was found to have a negative correlation by VonderAhe.
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2.7.2.4 Bone density

Historically, the use of areas of increased bone density such as the labial or palatal cortical plate were thought to be good for increasing anchorage during treatment mechanics.

Ten Hoeve and Mulie\textsuperscript{100} were the first to report an association between root contact with the bony cortical plate and OIIRR. Horiuchi et al\textsuperscript{101} found root approximation to palatal cortical plate during retraction of incisors to be factors influencing the amount of root resorption. Narrowing of alveolar bone width was also influenced apical root resorption.

In contrast, the amount of alveolar bone around the root of a tooth, the thickness of cortical bone and density of trabecular network have not been found to have significant correlation with the extent of OIIRR.\textsuperscript{102} Mirabella and Artun\textsuperscript{84} reported a few cases in their sample to have root contact with the palatal cortical plate without significant root resorption. They suggested that resorption may be more dependent on the amount of tooth movement than pressure on the cortical plate.

2.7.2.5 Specific tooth vulnerability to root resorption

OIIRR can present as localised to particular teeth or as a generalised shortening of all the teeth. Regardless of genetic or mechanical related factors, it is generally agreed that maxillary incisors seem to be affected by OIIR more frequently and to a greater extent than the rest of the dentition\textsuperscript{62,88}. A possible reason is that the maxillary incisor is most often moved the greatest distance through bone and subjected to longer active force duration than any other tooth.\textsuperscript{10} Maxillary central incisors are usually quoted as more affected than the maxillary lateral incisors. However, some studies have reported the lateral maxillary incisor as the most affected tooth\textsuperscript{5,103}. 

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Sameshima et al suggest that this was due to the lateral incisors having a higher incidence of abnormal root shape.\textsuperscript{103}

Other teeth vulnerable to OIIRR are the mandibular incisors, distal root of the mandibular first molars, mandibular second premolars, and maxillary second premolars.\textsuperscript{5}

Peg shaped laterals have not been associated with an increased risk of OIIRR.\textsuperscript{84}

Root resorption has been reported to range from 0\% to 90.5\% of examined teeth or 0\% to 100\% of examined patients in the untreated population\textsuperscript{5,35,58-59,61,104-108}. The presence of root resorption on teeth prior to orthodontic tooth movement significantly increases the risk of further resorption during orthodontic treatment.\textsuperscript{80,91}

### 2.7.3 Mechanical factors

Mechanical risk factors associated with OIIRR are those related to the type of orthodontic treatment mechanics used to move teeth. Many treatment related risk factors have been studied such as force characteristics, type and direction of tooth movements, treatment duration and orthodontic appliance factors. As these factors are under the clinician’s control, knowledge in this area may allow for minimisation of OIIRR.

#### 2.7.3.1 Force characteristics

Mechanical risk factors which may possibly be preventable such as the magnitude of force used or the duration of force have been investigated.
Continuous, interrupted continuous and discontinuous forces have been compared. It has been hypothesised that periods of rest may allow for secondary cementum to repair resorption cavities.\textsuperscript{27} Harry and Sims\textsuperscript{39} suggested that duration of force was more crucial than magnitude in regards to root resorption.

Dermaut and demunck\textsuperscript{108}, however, said there was no significant relationship between duration of force and root resorption.

Owman-moll\textsuperscript{109} compared the effect of continuous 24 hours/day vs. interrupted continuous (interrupted one week every four weeks) forces in adolescents. Histological sections of the experimental teeth showed no difference in amount or severity of root resorption between the two forces.

In contrast, Maltha and Dijkman in an animal study found discontinuous forces (16 hours per day) caused less extensive root resorption when comparing the amount of root resorption after (24 hours per day) forces.

Acar et al\textsuperscript{110} compared the effect of 100g tipping force on 22 experimental premolars using elastics continuously for 24 hours vs. 12 hours on the discontinuous side. After 9 weeks, the mean percentage of resorption affected areas was smaller and apical blunting was less severe on the discontinuous side.

It is generally thought that increasing force magnitude would be associated with an increase in root resorption as it would lead to more areas of hyalinisation. It is also believed that higher forces cause more extensive root resorption because the rate of lacuna development is more rapid and the tissue repair process is compromised.\textsuperscript{4,10}

Dellinger\textsuperscript{111} and reitan\textsuperscript{27} reported increased root resorption with increasing force magnitude.

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Owman moll et al\textsuperscript{112} in their histological study did not agree. They found root resorption was not force sensitive as forces of 50g and 100g applied to maxillary first premolars produced no significant difference in the severity of root resorption. The same group of researchers also compared 50g with a four fold larger force of 200g\textsuperscript{113}. No significant differences in the frequency or severity of root resorption were found between the two forces used.

2.7.3.2 Type of orthodontic movement

All types of orthodontic tooth movement induced some form of root resorption. Tipping, torque and bodily movement of teeth have been implicated as mechanical risk factors\textsuperscript{80,99,114}. Intrusion of teeth seems to be the most detrimental movement in terms of root resorption\textsuperscript{104,108,115} as this movement concentrates pressure at the tooth apex. Expansion with RME has also been identified to cause root resorption\textsuperscript{51}.

2.7.3.3 Correction of impacted maxillary canines

Impacted maxillary canine treatment has been identified as a risk factor for apical root resorption of incisor teeth. This is not just confined to the root of the adjacent lateral incisor and can not be fully explained by the ectopic eruption path of the canine. Linge et al\textsuperscript{9} theorised that the extrusive of the canine would cause a reciprocal intrusive force on the incisors. Intrusion of maxillary incisor teeth have been associated with considerably more apical root resorption in orthodontic patients.\textsuperscript{108}
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2.7.3.4 Arch wire sequence

Mandall et al.\textsuperscript{93} in a randomised controlled trial aimed of one hundred and fifty four patients compared the differences between three orthodontic archwire sequences in terms of patient discomfort, root resorption and time to working archwire. They found no statistically significant difference between archwire sequences for patient discomfort or upper incisor root resorption.

Begg vs. Straight wire vs. standard edgewise

No statistical difference in tooth length could be found after Begg, Tweed or straight wire techniques.\textsuperscript{114}

2.7.3.5 Two phase class II treatment

Brin et al.\textsuperscript{92} tested the hypothesis that the maxillary incisors of class II children treated in a single phase with fixed appliances were more likely to experience moderate to severe OIIRR. It was thought that single phase treatment would involve a longer time in fixed appliances as well as greater root movement. A retrospective sample of 138 children compared single phase fixed appliances with two phases with headgear or bionator followed by fixed appliances. When examining the amount of root resorption of central and lateral incisors, significant associations were made among OIIRR and the magnitude of overjet reduction and the time spent wearing fixed appliances. They concluded that early growth modification to reduce the severity of an overjet might play a role in decreasing the incidence of OIIIRR in class II malocclusion patients.

The use of herbst function appliance for treatment of class II malocclusion may deliver unphysiologic forces to the immediate anchor teeth thereby exposing them to a high risk of root resorption.\textsuperscript{116}
2.7.3.6 Self ligation

With the introduction of self ligating brackets, many claims have been made about the increased efficiency of tooth alignment compared to conventional brackets. This is most likely due to lower friction levels reported with the use of self ligating brackets. Scott et al.\textsuperscript{117} examined the clinical effectiveness of self ligating versus conventional preadjusted edgewise orthodontic bracket systems as well as the effect on mandibular incisors. Their randomised controlled trial reported no significant difference in the initial rate of tooth alignment. Incisor root resorption was not clinically significant and did not differ between different bracket types.

These results were also reported by Pandis et al.\textsuperscript{118}, who found no difference in the amount of OIIRR between conventional and passive self ligating brackets.

The use of elastics such as in the case of class II correction may be a risk factor for the teeth that support the elastics.\textsuperscript{9,84} Mirabella et al.\textsuperscript{84} suggested that it was probably due to the jiggling movements that occur on these anchor teeth.

2.7.3.7 Extraction treatment

The literature is inconclusive regarding the effect of extraction treatment on OIIRR. No difference between extraction and non extraction has been reported by VonderAhe\textsuperscript{99} from 57 patients.

Some studies have reported that a positive correlation between OIIRR and extraction treatment may exist. Sameshima and Sinclair\textsuperscript{103} observed that patients who had undergone all first premolar extraction experienced more root resorption than patients who had non extraction or only maxillary first premolar extractions.
McNab et al\textsuperscript{119} reported a higher incidence of OIIRR when treatment was performed with Begg appliances compared to edgewise appliances. When extractions were performed, the incidence of OIIRR was 3.72 times higher.

Patients who have extraction treatment with the correction of open bite may be more prone to OIIRR. This may be due to the amount of overjet correction and retraction of central incisor apices.\textsuperscript{120}

Extraction space closure using 2-step sliding mechanics (canine retraction first then incisor retraction) and en mass space closure has been investigated in 52 patients by Huang et al. It was postulated that since two step space closure takes longer to close an extraction space than an en masse procedure, it may be associated with more frequent and serious OIIRR. Their study, however found no significant difference in root resorption between two step and en masse space closure procedures.

Early Serial extraction followed by mechanotherapy has previously been hypothesised to cause less OIIRR due to the procedure needing less mechanotherapy since crowding of incisors would be relieved. A qualitative study comparing serial extraction vs. late extraction found the serial extraction patients to have less OIIRR, however, it was not clinically significant\textsuperscript{121}. Brin and Bollen\textsuperscript{122} also compared serial extraction vs. late extraction cases with similar amounts of tooth movement. They concluded that the spontaneous unravelling of incisor crowding with serial extraction treatment did not prevent OIIRR and that the differences in tooth length reduction between the two groups were not significant.
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2.7.3.8 Removable vs. fixed appliances

There is still debate in the literature regarding which treatment appliance, fixed or removable, is associated with more OIIRR.

Linge and Linge reported less root resorption in their removable appliance group than the group treated with fixed appliances. However, they stated that the risk of root resorption must be weighed against appliance efficiency and individual treatment objectives.

This use of thermoplastic aligners has increased in popularity as an alternative to treatment with fixed appliances. In terms of root resorption, Barbagallo et al. compared sequential removable thermoplastic aligners with both light and heavy forces from conventional fixed appliances. Root resorption volumes were measured from data produced by micro ct scans. It was found that thermoplastic aligners produced similar effects on root cementum as light (25g) forces from fixed appliances.

2.7.3.9 Treatment duration

Most studies have found a positive correlation between increased treatment duration and the amount of root resorption experienced by a patient. Liou et al, in a study of 50 adult patients, investigated apical root resorption of maxillary incisors in cases with en-masse maxillary anterior retraction and intrusion with miniscrews. They reported that apical root resorption of the maxillary central incisors was significantly correlated to the duration of treatment and not to the amount of en-masse retraction, intrusion or palatal tipping of the maxillary incisor teeth. They concluded that since more enmasse anterior retraction was needed with miniscrew anchorage cases, treatment time increased which might increase the risk of OIIRR.
Although this factor is most often correlated with apical root loss, publications by Baumrind and Koran \(^{87}\) and Mirabella and Artun \(^{84}\) have reported no significant association between treatment duration and OIIR.

Artun et al \(^{125}\) also reported that treatment duration and time with square arch wires was not related to the amount of resorption. The best predictor of severe apical root resorption in their sample seemed to be the amount of resorption experienced by the patient in the initial treatment stages. Orthodontic patients who experienced detectable root resorption in the first six months of active treatment seem to be more prone in the following six months than those without. \(^{126}\)

2.8 Management of OIIR

Patients must be informed of the risk of root resorption prior to starting orthodontic treatment as part of informed consent. In most cases, clinically significant shortening of a tooth root is rare. However, each patient must be made aware that, at present, we can not predict which individuals will be susceptible to severe root resorption. Significant loss of tooth root structure can lead to an unfavourable crown to root ratio. Many clinicians fear that the potential consequence is an adverse effect on the long term prognosis of the affected tooth. Current literature, however, suggests that even extensive root resorption does not usually affect the functional capacity or greatly compromise the longevity of the teeth. \(^4\) The reason for this may be in the initial stages of root resorption and crestal bone loss, 3mm of root resorption is approximately equivalent to 1mm of crestal bone loss. Following more than 2mm of loss, the ratio is closer to 2mm of root resorption equalling 1mm of crestal bone loss. \(^{127}\)
Various authors have suggested methods to minimise OIIRR. These include the use of light intermittent forces\textsuperscript{21,39,48}, reduction of treatment duration\textsuperscript{104,128}, habit control\textsuperscript{62,90} and prior assessment of family and medical history\textsuperscript{6,8,62,115}. Minimising the use of intermaxillary elastics\textsuperscript{9} and high risk tooth movements such as intrusion and root torquing have also been recommended\textsuperscript{114}.

Full radiographic records should be taken prior to commencement of treatment to aid in diagnosis and assess the preoperative root structures. Progress radiographs taken six to twelve months after the commencement of orthodontic treatment to detect early signs of OIIR\textsuperscript{4}. Levander and Malmgren found that root resorption of the upper incisors during the initial six to nine months of treatment with fixed appliances gives a high risk for continued resorption during the subsequent treatment.\textsuperscript{128}

If severe loss of root structure is detected, treatment objectives for the patient should be reassessed and a decision made on whether treatment should be stopped early or to reach an occlusal compromise. Active treatment should cease for 2 to 3 months with passive arch wires to decrease further root resorption and allow for reparative processes to occur.\textsuperscript{94} Alternative treatment options should be sought to decrease the time in fixed appliances such as prosthetic replacements to close space, and stripping teeth instead of extracting.

After active orthodontic treatment has been completed, further shortening of root structure will normally cease\textsuperscript{99}. This is to be expected as OIIR is a tissue-pressure response.

Remington et al\textsuperscript{88} found teeth that resorbed during orthodontic therapy frequently had rough, jagged, and often notched root contours. After a mean 14.1yrs long-term evaluation, no apparent increase in root resorption was detected, however, remodelling of rough, sharp resorption areas was evident.
2.9 Research methodologies

2.9.1 Methods for measuring OIRR

The methods used to study root resorption include radiography, serial sectioning and light microscopy\textsuperscript{48} and scanning or transmission electron microscopy\textsuperscript{129-130}. More recently micro computed tomography\textsuperscript{131-134} has been used for their ability to quantify variables in three dimensions. The current ‘gold’ standard in the measurement of root resorption volumes is with micro computed tomography\textsuperscript{12-14}.

Early studies on root resorption craters have used two dimensional methods such as radiographs, light or scanning electron microscopy to detect root resorption before, during and after orthodontic treatment. However, these methods have proven to be inaccurate in quantifying resorption craters due to problems of magnification, angulations and positioning errors and also reproducibility to allow comparison.

2.9.1.1 Radiography

Reports in the study of root resorption using radiographs have been performed with periapical or panoramic radiographs or lateral cephalograms. These reports are limited to assessing root resorption by apical root shortening. Surface resorption is usually very difficult to exam on radiographs as it must be sufficiently advanced or severe and at the correct angulations. Clinically, radiographs allow a clinician to detect the presence of root shortening before, during or after orthodontic treatment. The quantitative value of radiographs remains questionable.\textsuperscript{11}
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Periapical films have been found to be superior to panoramic images for fine detail and less distortion. Magnification of periapical films tends to be less than 5\%\textsuperscript{135}. Ideally positioning of the periapical radiograph should be performed using the paralleling technique to ensure geometrically accurate images\textsuperscript{136}. The bisecting angle technique tends to be unsuitable for root resorption assessment as it is difficult to reproduce views over time. Remington et al reported that root lengths can not be recorded from non standardised bisecting angle technique radiographs\textsuperscript{88}.

Panoramic radiographs tend to be used as screening tools of the dentition. A possible limitation of the use of panoramic radiographs is that root shapes such as dilacerations and other abnormal shapes are much harder to assess on panoramic films when compared to periapical views. Sameshima and Asgarifar\textsuperscript{137} in comparing periapical films to panoramic films found panoramic films to overestimate the amount of root loss by 20\%. Mandibular incisors are most likely to be vulnerable to this distortion. It was concluded that in cases where the apices are obscured, periapical films should be ordered.

Since root resorption craters are three dimensional in nature, Chan et al\textsuperscript{11} looked at using 3D scans to evaluate and quantify the volume of these craters.

In a comparison between periapical radiographs and micro ct images, Dudic et al\textsuperscript{138} concluded that apical root resorption may be underestimated when using digitised periapical radiographs.

\textbf{2.9.1.2 Serial sectioning and light microscopy}

This method has been used to study root resorption and repair. It involves embedding and serial sectioning an extracted tooth parallel to the long axis and histological staining such as with haematoxylin and eosin. Using a light microscope, quantification of resorption craters is made using
a micrometer fitted into the eyepiece. The major limitation of this method is that root resorption craters may be completely missed due to the sectioning process. Craters that are found could be miscalculated.

2.9.1.3 Scanning electron microscopy (SEM)

Reitan suggested that scanning electron microscopy provides enhanced visual and perspective assessment of root surfaces. When recorded in stereo pairs, they provide resolution and detail not attainable with histological models reconstructed from serial sections.

Kvam was the first to use SEM when documenting root resorption craters following tooth movement. Later studies by using SEM to measure root resorption used surface area landmarks obtained from micrographs. The problem with this method is that the root surfaces of the experimental teeth are curved and an absolute straight on view is difficult to obtain. Parallax errors in 3D can occur which would induce measurement errors. Also, the composite micrographs obtained are usually physically pieced together before resorption craters are measured with a digitiser. If craters occur along the edges of the micrographs, quantitative measurements would be inaccurate.

2.9.1.4 SEM stereo imaging and 3D measurements

To overcome this problem, Chan et al used the SEM as a capturing device and analysed stereo images of resorption. The pair of stereo images was converted into an 8 bit greyscale depth map. Volumetric measurements were calculated using specially written software. The planar area of the
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crater was multiplied by the average depth of the nominated crater to give the volume. This method was calibrated against a Vickers hardness tester indenting on four cylindrical metallic rods\(^4\). The results showed volumetric measurements by the software were both highly accurate and reproducible.

This method was later used to quantify root resorption in a sample of 36 teeth\(^4\).

2.10 Micro Computed tomography

X-ray microtomography is a non-destructive imaging method particularly useful in the biomedical field for assessing hard tissues. It is derived from computerised axial tomography and has a high spatial resolution in the order of micrometers. The first x-ray microtomography apparatus was introduced ten years after the CT scanner in 1982 by Elliot and Dover\(^4\). It has the ability to accurately measure and map on a microscopic scale and quantify structures in three dimensions. Current technology limits the use of microcomputer tomography to mainly small inanimate specimens such as bone or teeth\(^4\).

2.10.1 History and development of 3D microtomography

Wilhelm Conrad Roentgen was to first to discover the new form of radiation which he called x-radiation due to its unknown nature. He first presented his findings in 1895 to the Wursburg Physical Medical society in 1895. Although x-rays allowed non-invasive visualisation of the inside of the body, interpretation of the x-ray image was not simple. This was due to the loss of depth information as the features of a 3D object become superimposed as it is mapped onto a 2D image.
Computed axial tomography, introduced by Hounsfield in 1973 was a major advancement in the medical field as it made it possible for imaging of internal features to be based directly on their x-ray attenuation coefficients. Tomography involves taking a series of x-ray projections through the slice at various angles around an axis perpendicular to the slice. A 3D map of object can be obtained by computing the number of slices together.

The development of microtomography was aimed at scaling down the conventional medical scanner and allowing for the study of small specimens at high resolution. Current x-ray micro tomography scanners can produce an image resolution typically at 5 to 10 µm but also as far down as 1 µm. Besides the scale of the machine, the only other difference between medical CT scanners and microcomputer tomography is that the specimen moves whilst the x-ray source and detector are stationary for micro ct systems instead of the x-ray source moving around the subject in medical CT scanners. The cone beam algorithm introduced by Feldkamp in 1984 allowed for an easier tomographic reconstruction from 2D projection data. Its performance was shown to be faster and generally comparable to the standard fan beam algorithm.

### 2.10.2 SkyScan 1172 Desktop X-ray Micro Tomograph

This study makes use of the SkyScan 1172 micro tomograph (SkyScan, Aartselaar, Belgium) to examine the premolar samples. Previous root resorption studies performed at the Sydney University Orthodontic Department have used this machine in their analysis.

The SkyScan 1172 is a fourth generation compact desktop machine used for microscopy and micro tomography applications.
It consists of an X-ray shadow microscope system and tomographic reconstruction software. The cone beam X-ray source has a spatial resolution of 2 to 5 µm. The recommended image field is 68mm wide and 70mm high. Samples are placed in the system on a rotating platform which can revolve up to 360 degrees. Magnification is determined by the distance of the platform from the X-ray source. The X-ray detector consists of a high resolution 1024 x 1024 pixel charged couple device which can output generated 16 bit Tagged Image File Format (TIFF) picture files.

After image acquisition is completed, software based on Feldkamp cone beam algorithms reconstructs the axial slice by slice images. The resultant axial 2D images are generated as 8-bit greyscale 1024x1024 pixel bitmap (BMP) images.

Software program VG Studio Max (version 1.2 Volume Graphics, GmbH, Heidelberg, Germany) is used to collate the axial 2D slices to form 3D reconstructed images.

### 2.10.3 Previous research OIIR investigations using Micro CT technology

There are numerous studies in the literature using Micro CT technology to analyse OIIR, many of which have been performed at the Sydney University Orthodontic department.

Harris et al, in a prospective randomised clinical trial used a split mouth design to intrude upper first premolar teeth with no force (control), light force (25g) and heavy force (225g) for twenty eight days prior to extraction. They used the SkyScan – 1072 microcomputed tomograph x-ray system and specially designed software for direct volumetric measurements of OIIR craters. The volume of resorption crater was found to be directly proportional to the magnitude of the intrusive force applied with the light force and heavy force groups experiencing 2 and 4 times greater OIIR craters than the controls respectively.

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Foo et al hypothesised that since fluoride has been reported to be beneficial in preventing root resorption in dental traumatology, it may perform in a similar fashion in OIIR. Orthodontic force was used and fluoridated water was given to control and experimental wistar rats. After two weeks, the animals were sacrificed and the teeth scanned with the SkyScan 1072. Software analysis of the scans provided volumetric measurement of the OIIR craters.

Systemic fluoride was found to reduce the size of resorption craters however, this was variable and statistically insignificant (P>.05).

Barbagello et al used Micro CT to quantify the effect of clear sequential removable thermoplastic appliances (TAs) on OIIR craters. They also compared forces applied by clear sequential removable plastic aligners and fixed orthodontic appliances. 27 patients with 54 maxillary 1st premolar teeth were used as the sample. These subjects were randomly assigned to 3 groups consisting of 9 patients each. A split mouth design was used for each group. Group 1 used clear plastic aligners to move teeth on one side in a buccal direction at a rate of 0.5mm every 2 weeks while the contralateral side had no tooth movement and acted as the control group. Group 2 used clear plastic aligners for tooth movement on one side and beta-titanium alloy cantilever spring used to produce a heavy (225g) buccally directed force on the contralateral side. Group 3 was similar to group 2 except a light buccally directed force (25g) was used from the cantilever spring. The results found teeth undergoing orthodontic tooth movement had significantly greater root resorption than the control group teeth. Heavy forces (225g) produced significantly more root resorption than light forces (25g) or TA force. Light force fixed appliances and TA force produced similar effects on root cementum.

Continuing from these initiation studies, a series of split mouth studies using similar methodology and micro ct volumetric analyses looked at continuous vs. intermittent controlled orthodontic forces on OIIR, repair of resorption craters 4 and 8 weeks after 4 weeks of continuous light and heavy forces, the incidence of physiological root resorption on unerupted third molars, the amount of
root resorption after 12 weeks of light or heavy forces and OIIR after 2.5 and 15 degrees of buccal root torque for 4 weeks.\textsuperscript{146}

These studies reported increase in OIIR with increasing force (more in heavy 225g vs. light 25g) and increase in force duration over 4,8 and 12 weeks. Maxillary first premolars were more likely to suffer from OIIR than mandibular first premolars\textsuperscript{134}.

No significant difference in the amounts of repair of resorption craters was found at 4 or 8 weeks after 4 weeks of continuous force. Repair seemed to be steady after 4 weeks of passive retention following 4 weeks of light force application, whereas most repair occurred after 4 weeks of passive retention following 4 weeks of heavy force application.\textsuperscript{147}

Intermittent forces (4 days of force with 3 days rest) produced less root resorption on maxillary first premolars than continuous force over an 8 week period. Although it may not be clinically practical, intermittent forces might be a safer method to prevent significant root resorption.\textsuperscript{146}

Physiological root resorption was found in unerupted non-impacted maxillary third molars and compared with premolar teeth from the other studies which had undergone light and heavy orthodontic forces. It was found that unerupted third molars had slightly greater cube root volume per tooth than the erupted first premolars not subjected to orthodontic force and a similar cubic root volume per tooth as first premolars subjected to light buccal and intrusive forces. It was concluded that root resorption might occur as part of hard tissue remodelling and turnover.

Third order torque movements have been identified as a mechanical risk factor for OIIR. Increase in torque was found to produce more OIIR particularly in the apical region.\textsuperscript{132}

Da Silveira et al\textsuperscript{149} used an in vitro study aimed to evaluate the diagnostic ability of CT to detect simulated external root resorption defects in 59 human mandibular incisors. Cavities were drilled to standardised small, medium and large defects in the cervical, middle and apical thirds of buccal
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surfaces. They concluded that CT diagnostic ability revealed high sensitivity and excellent specificity, however, small cavities in the apical third were more difficult to detect than all other cavities.

Dudic et al\textsuperscript{138} compared the use of digitised periapical radiographs in evaluating OIRR against micro computed tomograph scanning as a criterion standard. 29 premolars from 16 subjects were tipped buccally for 8 weeks while 19 contralateral premolars not subjected to orthodontic movement acted as controls. They found that less than half of the cases with root resorption identified using a CT scanner were identified by radiography and thus concluded that evaluation of OIRR may be underestimated when evaluating with periapical radiographs.

2.11 Disinfection and Storage medium of experimental teeth

Malek et al\textsuperscript{150} in 2003 examined the effect of five different disinfection and storage protocols on the hardness and elasticity modulus of human premolar teeth. They found that Milton’s solution for 10 minutes was an appropriate method for disinfection and removal of the periodontal ligament remanent; however storage for 24 hours caused a significant decrease in the hardness of cementum. Storage in 70% alcohol or Milli Q solution was suggested as better alternatives for storage. Milli Q solution in particular was found to have no significant effect when used to store teeth for up to 9 months. Desiccation of tooth samples should be avoided as it was found that it caused a significant increase in both hardness and elastic modulus from baseline.
3 Vibration

Vibration, otherwise known as high frequency, low magnitude stimulation, is defined as a mechanical stimulus characterised by an oscillatory motion. The key descriptors of vibration include:

i) Frequency (measured in Hz; the number of Hz indicates the number of complete up and down movement cycles per second)

ii) Amplitude (the extent of the oscillatory motion, measured in mm)

iii) Direction of the vibration movement.

3.1 Whole body vibration

The study of vibration for achieving therapeutic or physical performance goals in the medical field has been increasing since the mid 1980s. Studies on the application of whole body vibration on the skeleton have been carried out in animals and humans; the therapeutic value of vibration being based on Wolff’s law – that, trabecular bone adapts to its mechanical environment. It is also thought that extremely small mechanical strains are strong determinants of bone morphology.\(^\text{151}\)

Rubin et al 2001 reported that low magnitude mechanical signals induced at a high frequency can stimulate bone formation. Vibration therapy has also been used to improve or maintain bone and muscle mass in cases such as mobility impaired patients\(^\text{152}\), decreased bone density\(^\text{153-154}\) and in surgical healing\(^\text{155-156}\). Whole body vibration has been studied as a possible means of decreasing the bone density loss that occurs in astronauts who have extended periods of time in space, or patients with extended bed rest.
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or paralysis\textsuperscript{157}. The advantage of vibration therapy is that it is non invasive, non pharmacological and can be applied in a low impact manner which is critical in elderly or diseased individuals.

There are currently many devices available for use in the fitness and health care areas. The frequency of vibration in these devices tends to range from a few Hz to 50 Hz with amplitudes ranging from a few micrometres to several millimetres.\textsuperscript{158}

The vibration protocol is very important. Stimulation of cortical bone in animal turkey study has been found to successfully stimulate an increase in cortical bone at high frequency 30Hz, low amplitude (200 microstrain) while low frequency 1Hz, high amplitude 3000 microstrain signals failed to anabolic\textsuperscript{159}. In a longer term animal study, 20 minute daily sessions of high frequency (30 Hz) and low level 0.3g(earth’s gravitational) force, stimulated 43% increase in bone density in the proximal femur\textsuperscript{151}

The AcceleDent is able to produce vibration variables of 30Hz and 20 grams. This is a vibration protocol is similar to that used by Rubin et al\textsuperscript{160} in the prevention of postmenopausal bone loss. Also, the Juvent 1000 vibration plate which works at 0.3G (force of gravity) at 32-37 Hz. This device has been reported to maintain the musculoskeletal system and is well within the exposure limits recommended by the international organisation for standardisation (ISO).

A Review by Prisby et al 2008\textsuperscript{161} looked at the skeletal effects of vibration in animals and humans. They noted that although the scientific basis of vibration devices is increasing steadily, current literature is unable to establish an optimal vibration prescription.
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This is due to a lack of standardisation in vibration parameters and methodology. Additionally, the lack of justification offered for the choice of vibration parameters is a significant limitation in the current literature.\textsuperscript{161-162}

Future research is needed to develop the optimal vibration protocol. This optimal protocol is likely to vary depending on the population using the vibration (e.g. young vs. elderly) due to differences in patient bone quality and bone remodelling patterns as well as the responsiveness of skeletal tissue to the vibration stimulus.

3.2 The use of vibration in dentistry and orthodontics

High frequency, low magnitude vibration has been applied in the field of orthodontics with the main aim of increasing the rate of orthodontic tooth movement by accelerating periodontal and bony tissue modelling/remodelling. Many authors have also hypothesised that vibration may also be a means of decreasing orofacial pain or pain associated with orthodontic adjustments.

3.2.1 Vibration and the rate of orthodontic tooth movement

The orthodontist’s aim is to achieve their treatment objectives for a patient as well as limit the duration of treatment and the amount of time a patient has braces on their teeth. In the literature, increased treatment duration has been associated with an increased risk of caries\textsuperscript{6}, periodontal problems\textsuperscript{7} as well as a higher risk of root resorption\textsuperscript{80,128}. 
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Roberts et al\textsuperscript{163} considered bone resorption at the PDL surface to be the rate limiting factor in orthodontic tooth movement. A maximal rate of molar translation in the maxilla is approximately 2mm per month of space closure in a rapidly growing child or 1mm per month of space closure in a non-growing adult. \textsuperscript{164} Clinically and experimentally there have been many attempts to increase the rate of orthodontic tooth movement, whether it be by reducing friction in the orthodontic appliances\textsuperscript{165}, adjunctive medicinal or hormonal therapies (local or systemic)\textsuperscript{166} and more recently surgical corticotomy techniques\textsuperscript{167}.

Previous research into these strategies has revealed some disadvantages. Systemic medicines can be non-specific and may produce unwanted side effects in addition to accelerating tooth movement. Local injection of drugs can complicate treatment and may cause discomfort for patients. Corticotomy techniques are invasive and increase patient discomfort.

Vibration has the advantage of minimal side effects in comparison to medicinal treatments. It also has proven to be a safe low impact alternative that enhances bone remodelling in the medical field.

Research on vibration and orthodontic tooth movement has mainly been applied to animal studies, in particular, rats. It is difficult to extrapolate the results of animal studies to humans due to differences in PDL and alveolar bone morphology and physiology. However, even with these shortcoming, rats are still generally considered to be a good model to study orthodontic tooth movement. \textsuperscript{168}

Darendeliler et al 2007\textsuperscript{169} studied the effect of high frequency low magnitude vibration in 44 wistar rats using magnets and a pulsed electromagnetic field. They hypothesised that since the literature
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has noted an increase in anabolic activity in bone from high frequency low magnitude vibration, it may also increase the rate of tooth movement.

The study was designed to allow a pulsed electromagnetic field to interact with Nd-Fe-B magnets bonded onto the molar teeth of the rat subjects. This interaction caused a mesiodistal vibration stimulus on the studied teeth. Having split the sample into 4 groups, they compared the effect of vibration alone; vibration compared with vibration and coil spring; PEMF alone compared with PEMF and coil spring; and vibration and coil spring compared with PEMF and coil spring.

The results showed coil springs, either with sham or active magnets move the molar teeth more than magnets alone regardless if a PEMF was present. Under a PEMF, the coil spring produced significantly more tooth movement than the coil-magnet group, as did the magnet group compared to the sham magnet group.

The authors concluded that the PEMF induced vibration may enhance the effect of mechanical and magnetic forces on tooth movement.

In another laboratory study by Nishimura et al\textsuperscript{170} in 2008, molar vibration in the rat model significantly increased the rate of tooth movement when compared to a non vibration control sample. This study was performed on a sample of 42 wistar rats with an experimental duration of 21 days.

Their vibration protocol (60Hz, 1.0m/s\textsuperscript{2}) was based on measuring the natural frequency of the rat first molar. The natural frequency or otherwise known as the resonance frequency was defined as the maximum recorded velocity in the resonance curve and was thought to be the force that applied the largest amplitude of vibration to the periodontal tissues.

Vibration Stimulation was only applied for 8 minutes which was determined in a previous pilot study of theirs to be the shortest period required to activate the periodontal ligament.

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In addition to reporting an increased rate of tooth movement, the authors also demonstrated the activation of the RANK–RANKL signalling pathway in response to the loading of resonance vibration. The safety of vibration was addressed by investigating the effect on root resorption. No significant differences in root resorption were found between the vibration and non vibration groups. In fact, they noted that a trend of less root resorption was found in the vibration group. The authors theorised that vibration may prevent hyalinisation of tissues in the PDL; however, further research is necessary to determine the exact mechanisms that take place.

3.2.2 Acceledent device

Following on from the findings of these studies, a device called the Acceledent, has reached the market and aims to achieve an increased rate of tooth movement by enhancing bone remodelling using pulsating forces. Its inventor, Dr Jeremy Mao previously investigated the effects of cyclic forces on suture growth. He based his studies on a model suggested by Meikle et al 1979 which concluded that cranial sutures models mimic the forces that the periodontal ligament and other sutures of the cranium are exposed to during orthodontic tooth movement.

The Acceledent vibration variables are based on Dr Rubin’s studies on whole body vibration with a frequency of 30Hz and amplitude of 20g. The Acceledent is prescribed to be used for 20 mins per day during orthodontic treatment and can be used as an adjunct to fixed appliance or aligner treatment.

With the release of this new device, research on the effectiveness and safety of vibration in humans for orthodontic tooth movement will be performed. Currently, there has been an initial study on the Acceledent device and its effectiveness on the rate of tooth movement and its effect on root
resorption performed at the UT-Houston in Texas, US. Results from these studies have been favourable, with the Acceledent groups showing an increased rate of tooth movement over controls as well as less root resorption when reviewed with cone beam CT images.

3.2.3 Pain and vibration

Pain is a common experience and concern for patients who undergo any form of dental treatment. Pain following an orthodontic adjustment has been reported to be quite prevalent and may affect patient compliance with treatment. Pain associated with orthodontics may also adversely affect the level of patients' plaque control.

The usual method of dealing with discomfort is with the use of analgesics. NSAIDS have been reported to decrease the rate of tooth movement and thus possibly increase orthodontic treatment times. In a systematic review on the effect of medicines on orthodontic tooth movement, it was suggested that paracetamol was the analgesic of choice as it didn’t affect the rate of tooth movement.

Other alternatives to analgesics for pain control include chewing gum after adjustments; Or the use of lower force levels. Even if lower force levels are used, Lim et al showed that pain was still experienced by most patients.

More recently low level laser therapy, transcutaneous electrical nerve stimulation and vibratory stimulation have been shown to be effective post orthodontic adjustment.

When using Vibratory stimulation it is thought that the vibration acts to interfere with the pain pathways, in particular, the interaction between large fibres and small pain-carrying fibres.
It also appears to re-establish the blood supply and intercept the ischemic response.\textsuperscript{179} Marie et al\textsuperscript{179} used a small battery operated vibrating motor with a soft detachable mouthpiece and observed that the appliance had to be used before the onset of pain for it to be effective. When used after pain had manifested, vibration did little to decrease it. They found, with the use of visual analog scales, that discomfort was significantly less at every time interval for those patients who used the vibratory apparatus.

### 3.2.4 Conclusion

Vibration in orthodontics is still in its infancy. Initial studies for increasing the rate of tooth movement have been promising. The reduction of pain associated with orthodontic adjustment when using vibration is another positive in its use.

With the introduction of the Acceledent device, the use of vibration in orthodontics could become more widely spread. More clinical trials will be needed to fully access the efficacy of Acceledent as well as its safety.

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The Effect of Mechanical Vibration (Acceledent, 30Hz) applied to the hemi-maxilla on Root Resorption Associated with Orthodontic Force

A Micro-CT Study

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4 ABSTRACT

Introduction

Root resorption is an unpredictable, unavoidable pathologic consequence that occurs during orthodontic tooth movement. Fortunately in the majority of cases, root resorption is minimal.

In the pursuit of increasing treatment efficiency and decreasing treatment duration, vibratory stimulation has been advocated as a possible adjunct to orthodontic appliances to increase the rate of tooth movement. Following this, a new device called the Acceledent has become commercially available, and is aimed at decreasing treatment duration by accelerating periodontal and bony tissue remodelling with low magnitude high frequency vibration. To date, there are few studies on the effect of vibration on root resorption during orthodontic tooth movement. The aim of this clinical study was to investigate the effect of Acceledent vibration on the volumetric amount of root resorption after the application of a controlled force (150g) in a buccal direction for 4 weeks.

Materials and Methods

Fifteen patients requiring bilateral extraction of their maxillary first premolar teeth as part of their orthodontic treatment were recruited for the study. With ethical approval and informed consent obtained, the experiment incorporated a split mouth design, with the left and right maxillary first premolars subjected to a buccally directed force of 150g using partial fixed appliances. Each patient was issued with an Acceledent device with only half a mouthpiece to use (side randomly assigned) for 20 minutes per day according to the manufacturer’s instructions. At the end of the 4 week experimental period, the premolars were extracted and scanned with microcomputer tomography.
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(micro CT). Volumetric measurements of the root resorption craters were performed with specially designed software.

**Results**

Individual variation was evident in the amount and distribution of root resorption craters. There was no statistical difference between the Acceledent vibration and non-vibration groups in terms of root resorption volumes and distribution $p =0.67$. Regression analysis investigating the relationship between the amount of root resorption in non-vibrated teeth and the improvement in root resorption with the use of vibration revealed a statistically significant trend $p = 0.029$.

**Conclusions**

The use of Acceledent did not appear to increase the volume of root resorption craters of maxillary first premolars that had undergone a buccally directed force for four weeks to a statistically significant degree. Vibration could potentially be more beneficial in patients who are more susceptible to root resorption during orthodontic tooth movement. Further research is necessary to validate the full effect of vibration using the Acceledent device on tooth root resorption.

Key words: Root resorption, Acceledent, vibration, x-ray microtomography, volumetric analysis
Introduction and literature review

Root resorption has long been recognised as an undesirable side effect of orthodontic tooth movement. It is the destructive process of the cementum and/or dentine layers of a tooth root due to clastic cell activity which may eventually lead to loss of apical root length. The term "Orthodontically induced root resorption (OIIRR)" was introduced by Brezniak and Wasserstein to describe the type of root resorption experienced during orthodontic treatment. It is an unavoidable and unpredictable pathological surface or transient inflammatory root resorption that occurs due to the presence of an orthodontic force on a tooth. Generally it is accepted that most individuals will experience some degree of root shortening after orthodontic treatment. Fortunately the presence of severe root shortening is relatively uncommon after orthodontic treatment.

Although the exact aetiological factors remain unclear, previous studies suggest possible risk factors for root resorption could be biological or mechanical in origin. Biological factors such as genetic factors, ethnicity, chronological and dental age, systemic factors, nutrition, gender, root morphology, and a previous history of root resorption have been indicated.

Treatment mechanic factors that have been suggested to cause an increase in root resorption are force magnitude, duration of orthodontic force, direction of tooth movement, and the type of tooth movement.

Increased treatment duration has been suggested as a significant factor in increasing the risk of root resorption. Prolonged treatment time in fixed appliances has also been associated with an increased risk of caries and periodontal problems. Many attempts have been made to accelerate orthodontic tooth movement and decrease overall orthodontic treatment times. These include systemic and local medications, corticotomy techniques and recently, low magnitude, high frequency vibration stimulation, or “Vibration therapy”.

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Vibration therapy has been increasingly studied in the medical field and has been successful in improving or maintaining bone and muscle mass in cases such as mobility impaired patients, decreased bone density and in surgical healing.

Stimulation of bone in an animal study using high frequency, low magnitude vibration has also been found to successfully stimulate an increase in cortical bone. When compared to low frequency 1Hz, high amplitude 3000 micro strain signals, vibration failed to be anabolic. In a longer term animal study, 20 minute daily sessions of high frequency (30 Hz) and low level 0.3g (earth’s gravitational) force, stimulated 43% increase in bone density in the proximal femur.

The Accelendent is a new device specifically designed to be used in orthodontics. It is able to produce vibration variables of 30 Hz and 20 grams. This vibration protocol is also similar to that used by the Juvent 1000 vibration plate which works at 0.3G (force of gravity) at 32-37 Hz used to maintain the musculoskeletal system.

In orthodontics, early animal studies on high frequency, low magnitude vibration were aimed at increasing the rate of orthodontic tooth movement by accelerating periodontal and bony tissue modelling/remodelling. Many authors have also hypothesised that vibration may also be a means of decreasing dental pain or pain associated with orthodontic adjustments.

Although vibration in conjunction with orthodontics may accelerate bone and periodontal tissue remodelling, there is very limited research on the effect of this accelerated remodelling on the root surface of teeth.

The aim of this study is to compare the root resorption that occurs on human upper first premolar teeth following the application of a buccally directed force (150g) with and without vibration, using the vibration device called “Acceledent”. The experimental teeth were extracted after four weeks of force application and examined using Micro-computed tomography. This method has been shown to be more accurate and reliable at quantitative measurements than previous studies using two
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dimensional radiographs, light microscopy and scanning electron microscopy and transmission electron microscopy. This study will be included as part of the series of root resorption studies performed at the University of Sydney.
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Materials and methods

The sample consisted of thirty maxillary first premolar teeth which were collected from a total of 15 healthy patients (6 boys, 9 girls; mean age, 15 years 8 months; range, 13 years 5 months – 21 years 7 months) who required these teeth to be extracted as part of their fixed orthodontic appliance treatment. Subjects were selected using a strict criteria previously described. All subjects and their parents or guardians consented to participation after receiving verbal and written explanations (ethics approval: SLHN No X11-0013 & HREC/11/RPAH/13).

Each subject had partial fixed appliances bonded to their maxillary posterior teeth (Figure 1). These consisted of 0.022-inch Speed brackets (Strite Industries, Cambridge, Ontario, Canada) bonded on the maxillary first permanent molar and the first premolar teeth. Self ligating brackets were used to provide standard ligation of the experimental teeth. Both sides received a buccally directed force of 150g using a 0.017x0.025-in TMA cantilever spring (beta III titanium, 3M Unitek, Monrovia, Calif). All cantilever springs were made by one clinician (DT) and no reactivation of the spring took place during the 4 week experimental period.

A strain gauge (Dentaurum) was used to measure the force magnitude and verified with two members of Sydney Dental Hospital orthodontic staff. The experimental premolar teeth were relieved of occlusal interferences by placing light cured cement (Transbond Plus light cure band adhesive, 3M Unitek) on the occlusal surfaces of the mandibular first permanent molar teeth.

Each subject was randomly assigned a side for which they would use the Acceledent device. This divided the premolar samples into “vibration” and “non-vibration” groups. The Acceledent mouthpieces were modified by cutting them in half so that the mouthpieces would only vibrate on...
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the side assigned to the subject (Figure 2). The subjects were then instructed to use the Accelecent according to the manufacturer’s instructions. This involved biting on the mouthpiece (light pressure) and using Accelecent vibration for 20 mins per day. The compliance with the Accelecent device was monitored using the inbuilt software of the device which records daily usage, as well as calling the patient by telephone to remind the patients to use the device.

After four weeks of using Accelecent vibration and force application, the cantilever springs were removed and the upper first premolars were carefully extracted by one of two surgeons. To minimise damage to the root cementum, no luxators were used and minimal contact was made between forceps and the cervical cementum. Each tooth was then immediately stored in separate specimen sample containers filled with sterilised deionised water (Milli Q, Millipore, Bedford, Mass). Milli Q has previously been described as an appropriate storage media for root resorption research.50

To prepare the teeth for analysis, residual PDL and soft tissues were removed by placing the teeth in an ultrasonic bath for 10 minutes. Any remaining soft tissue fragments were then removed by gently rubbing the root surface with a damp gauze swab. The teeth were then disinfected with 70% alcohol for 30 minutes and dried on the bench at ambient room temperature (23°C ± 1°C) for at least 48 hours.

The analysis of the root surfaces involved scanning the sample teeth with the SkyScan 1172 desktop x-ray microtomograph (SkyScan, Aartselaar, Belgium). This system produces high spatial resolution 2-dimensional x-ray shadow projections which allow for 3-dimensional reconstructed images.

All of the sample teeth were scanned separately from 2 to 3mm coronal to the cemento-enamel junction through to the root apex. The x-ray tube was operated at 60kV and 167µA. No filter setting was used with a resolution of 17.2µm pixel size. Teeth were rotated 360° around the long axis of the
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root at 0.2° rotational steps during the x-ray acquisition process. X-ray absorption radiographs were acquired at each rotation step producing a total of 1800 x-ray absorption radiographs for each tooth.

Each generated image was saved in 16-bit tagged image file format (TIFF) picture files.

Slice by Slice reconstruction was performed using SkyScan’s volumetric reconstruction software (Nrecon, version 1.4.2 Aartsellaar Belgium). The software program uses a modified Feldkamp algorithm to create a set of cross sectional slices through the tooth. Reconstructed slices are 1024 x1024 pixels having an 8 bit gray scale dynamic range, saved in BMP data format.

Visualisation and analysis of CT data is performed using VGStudio Max software (version 1.2, Volume Graphics, Gmbh, Heidelberg, Germany). This program allows for precise and fast analysis of voxel data. Root resorption craters are first viewed in the 3D reconstructed images and then verified in axial cross sections. Individual craters were isolated and then exported as axial slices to specially designed software (Convex Hull 2D, University of Sydney, Australia) to measure the volume of each crater (Figure 3).

Root resorption craters were grouped according to their location in the vertical plane e.g. apical, middle or cervical. This was performed by measuring the total length of the root from the CEJ to the apex and dividing it into equal thirds. Craters were further separated according to their location when viewed axially, namely, the buccal, palatal, mesial and distal surfaces. All measurements were carried out by one operator (DT) to eliminate inter-operator variability.
**Statistical analysis**

The volumes of the root resorption craters were measured as voxels and then converted to mm³ for analysis. This was performed according to the methods of previous micro-CT root resorption studies.²⁴,⁴⁸-⁴⁹,⁵¹

Root resorption crater volumes were summed together to obtain total resorption values per tooth. They were also grouped according to their position by facial surface (buccal, palatal, mesial, or distal) as well as by their placement in vertical third of the root (coronal, middle, apical).

Paired t tests compared the non-vibration and vibration root resorption crater volumes for each subject using statistics software SPSS (SPSS for windows version 19; SPSS, Chicago). All tests were analysed for a statistical significance level of p<0.05.

A regression analysis compared the total volumes of root resorption experienced by the non-vibration experimental teeth to the improvement in root resorption (measured by non-vibration root resorption volume minus vibration root resorption volume).

The root resorption crater volumes of six randomly selected teeth were remeasured to obtain a standard error of measurement (SE meas) and a coefficient of variation (CV %).
Results

The compliance with the Acceledent device was recorded using the inbuilt software of the base unit. At the end of the experimental period the range of patient compliance with Acceledent usage varied from 73% to 100% with a mean compliance of 92.5%.

Volumetric measurements of craters were repeated on six randomly selected teeth to obtain a standard error of measurement (se meas = 0.0056) and a coefficient of variation (CV=3.6%). When separated into non-vibration and vibration measurements, non-vibration se meas = 0.0045, CV=2.7%; vibration se meas = 0.0065, CV = 4.4%.

There was a wide variation in response to the Acceledent. The mean total amount of root resorption of the Acceledent experimental maxillary premolar was 0.1085 mm³. When compared to the non-vibration tooth group (0.095 mm³), the difference in root resorption volume was not found to be statistically significant, p=0.67 (Table I) (Figure 4).

When the results were analysed for location of the resorption craters according to vertical thirds, the differences were not statistically significant (p-values buccal = 0.46, mesial = 0.94, palatal = 0.86, distal =0.35). Facial surfaces of the roots showed little variation in the number and size of the resorption craters between the two groups (p-values cervical = 0.56, middle = 0.22, apical = 0.80).

A regression analysis was performed of improvement (measured by the difference of vibration from non-vibration volumes) on the total volumes of root resorption experienced by the non vibration group. The regression is statistically significant with p = 0.029 (Table II) (Figure 5).

Patients with higher non vibration root resorption volumes showed a significant increase in improvement of resorption values for buccal (p=0.12), palatal (p<0.001), cervical (<0.001) and apical

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(p=0.03) surfaces. The mesial (p=0.06), distal (p=0.09) and middle (p=0.07) regions of the root did not reach statistically significant levels but were all in the same direction.
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Discussion

The most commonly affected teeth from orthodontically induced root resorption are the maxillary incisors. In this study, upper first premolars were chosen as they are frequently extracted as part of orthodontic treatment planning and buccal tipping force was applied for four weeks to those teeth. The experimental duration was limited to four weeks due to ethical and practical reasons. Though this is much shorter than routine orthodontic treatment, this is consistent with studies performed previously, and despite the limited duration, root resorption craters were still evident on both vibration and control groups.

Daily courtesy telephone calls were made to subjects to encourage routine use of the Acceledent. However, the recordings from the Acceledent device indicated that 100% patient compliance during the experimental period was not achieved (mean compliance 92.5%). Vibration from Acceledent was instructed to be applied for 20 mins per day for the four weeks of the experiment. The basis for the time frame comes from vibration studies by Rubin et al. Although not related to orthodontics, they found two 10 minute vibration treatments per day to be effective in inhibiting the decline in bone mass density. Their main issue was compliance with their vibration plate with the highest quartile of compliance to be 86% compliant. They suggested compliance may have improved if a single 20 minute session had been used. Compliance with vibration was found to be a problem in this study even with the single 20 minute daily usage. Future research could possibly be directed at shortening the vibration period in order to avoid interfering with a patient’s personal schedule to further improve daily compliance of Acceledent.

Previous root resorption studies have reported a significant amount of resorption on the buccal-coronal and apical-palatal regions corresponding to a buccal tipping force. Compared to these findings, this study also found several craters on the mesial and distal surfaces of both the vibration and non vibration experimental teeth.
The presence of resorption lesions on the mesial and distal aspects of the teeth could indicate a rotational or torquing movement occurring concurrently to the buccal tipping of the teeth caused by the cantilever spring. This may have affected the amounts of root resorption craters experienced by the experimental teeth as slight differences in the initial malocclusion and root morphology would have affected which areas of the PDL were compressed and hyalinised by the orthodontic force.

Initial pilot studies on the Acceledent device and its effectiveness on the rate of tooth movement as well as its effect on root resorption have been performed at the University of Texas, US. Results from a case report\textsuperscript{55} have been favourable, with the Acceledent groups showing an increased rate of tooth movement over controls. Root resorption after 6 months of Acceledent use in conjunction with fixed appliances were found to be within clinically accepted limits\textsuperscript{56}. However, this cone beam study used a small sample and no mention was made of the overall compliance rate of the Acceledent during the 6 month study period.

Nishimura et al\textsuperscript{37} suggested that low magnitude, high frequency stimuli can accelerate orthodontic tooth movement with no collateral damage to periodontal tissues. Their animal research reported no significant difference between vibration and non vibration in terms of root resorption after 21 days. This was similar to the finding of this study; however, comparison is difficult due to differences in the vibration device and the experimental protocol which were used.

Interestingly, Nishimura et al\textsuperscript{37} did observe a trend towards less root resorption in the vibration group. Vibration has the potential to alter tissue perfusion, however the magnitude of this effect is tissue specific and depends on the vibration regimen\textsuperscript{57}. The authors hypothesised that vibration in their study may have prevented blood flow obstruction and the development of hyalinization, thus leading to less root resorption.
Using Micro CT imaging, this study did not produce enough evidence to show a difference between the vibration and non vibration groups. There was great individual variation in the amount and severity of root resorption for this study sample. This may possibly be explained by individual susceptibility to root resorption \(^7,16,58\). Another possibility is differences in response to Acceledent vibration. The subjects may have different responsiveness of skeletal and periodontal tissues and cells to vibratory stimuli as well as differences in patient bone quality and bone remodelling patterns.

Although no statistically significant trends for lower root resorption were found in the Acceledent vibration group, some subjects did appear to experience much less resorption when compared to the non vibration teeth.

The regression analysis comparing root resorption volumes in the non vibration teeth to the improvement in root resorption revealed a statistically significant relationship. It suggests that patients with initially higher root resorption predisposition (as measured by the root resorption volumes of the non vibration group) may potentially benefit more from the use of vibration than those that were less susceptible for root resorption. This finding may be useful in minimising future orthodontically induced root resorption in cases where patients present with a high amount of risk factors for root resorption prior to orthodontic treatment.

Further research with a larger sample size and longer study design may be needed to further investigate the effect of Acceledent vibration on root resorption and its mechanisms.
Conclusions

To date, there have been limited studies on the effect of vibration on orthodontically moved teeth and root resorption. From our results, we can conclude the following:

1. Individual expression of root resorption on buccally tipped upper first premolars was highly variable after the daily use of Acceledent for four weeks.

2. Acceledent vibration at the frequency and duration utilised in this experiment did not appear to increase or decrease the amount of root resorption experienced by teeth that were tipped buccally after 4 weeks to a statistically significant degree. Further testing is required to determine if difference frequency levels or daily vibration regimens may be more beneficial.

3. Vibration may potentially be more beneficial in patients more susceptible to orthodontically induced root resorption.

4. Further research is necessary to determine the full effect of vibration when used in orthodontics.

Acknowledgement

This study was supported by the Australian Society of Orthodontics Foundation for Research and Education Inc.

We wish to thank AB Orthodontics (Australia) and OrthoAccel Technologies for their generous donation of the Acceledent units used in this study.
The effect of mechanical vibration (Acceledent) on root resorption and tooth movement after application of orthodontic force. A micro−CT study.

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References


The effect of mechanical vibration (Acceledent) on root resorption and tooth movement after application of orthodontic force. A micro−CT study.

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40. Gusi N, Raimundo A, Leal A. Low-frequency vibratory exercise reduces the risk of bone fracture more than walking: a randomized controlled trial. BMC Musculoskeletal Disorders 2006;7:92.


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5 Appendix

Study design

N=15 patients

Acceledent vibration (20 mins per day)  Non vibration

n=15 premolars  n=15 premolars
Figure 1 (a&b) - Appliance Design

Figure 1 a. intraoral view of the experimental appliance

Figure 1b. TMA cantilever spring before ligation (left) and after ligation (right)

Figure 2 (a&b) - Acceledent device

Figure 2 a. Acceledent device with modified mouthpiece (mouthpiece side was randomly assigned)

Figure 2 b. Clinical use of Acceledent

Sky Scan 1172 Desktop X-ray Microtomograph

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Specimen Mounting on the SkyScan 1172 Desktop Microtomograph

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Skyscan 1172 x-ray images

Nrecon version 1.4.2 Aartsellaar Belgium
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Images from Cone Beam Reconstruction with NRecon (Aartsellaar, Belgium Version 1.4.2)

Figure 3: 3D reconstruction images using VG Studio Max (Volume Graphics, GmBh, Heidelberg, Germany)
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Convex Hull 2D

An imaginary line is drawn to enclose the crater on each slice of the extracted image.

The area bordered by this line and the outline of the resorption crater is calculated by the program.

The result is measured as Voxels. The actual volume of the resorption crater is the product of the Voxels and the scanning resolution.
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Table I (a&b) - Paired T tests

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<tr>
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Paired Samples Statistics

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Paired Samples Test

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<th>Sig. (2-tailed)</th>
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Figure 4: Graph - Vibration vs. Non-vibration

R² Linear = 0.003

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The effect of mechanical vibration (Acceledent) on root resorption and tooth movement after application of orthodontic force. A micro-CT study.

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**Table II (a&b) - Regression Analysis of mean volume difference (improvement) on non-vibration root resorption volume.**

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a. Predictors: (Constant), nvib
b. Dependent Variable: diff

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a. Dependent Variable: diff
The effect of mechanical vibration (Acceledent) on root resorption and tooth movement after application of orthodontic force. A micro-CT study.

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Figure 5: Graph – Improvement vs. Non-vibration

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## Raw Data – Patient information and total root resorption Volumes

### Total resorption per tooth mm³

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<th>Vibration Group</th>
<th>Non-Vibration Group</th>
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### Root resorption per tooth surface mm³ - Vibration group

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### Root resorption per tooth surface mm³ - Non vibration group

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### Root resorption per vertical thirds mm³ - Vibration group

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Daniel Tan

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Future directions

Vibration is a relatively new field. Although it has been studied increasingly in the medical field for the treatment of mobility impaired patients, decreased bone density and in surgical healing, little is known about the potential benefits for the orthodontist. Initial studies on the effect of vibration on orthodontic tooth movement and the craniofacial structures have so far been limited to animal studies.

With the introduction of Acceledent, the use of vibration in orthodontics may transfer from the theoretical, experimental use to common day usage.

This study is one of the first to look at the effect of Acceledent on root resorption while teeth are undergoing a buccally directed force. Its study design was based on similar methodology used in previous research work in the Sydney university orthodontic department.

To further assess the clinical safety of Acceledent, further research is needed with possibly a longer study duration and larger sample size.

This study was limited to extracted premolar teeth. The use of Micro CT limits its use to inanimate objects. As technology improves a Micro CT scanner may become available for live subjects. If this is the case, studies on the root resorption of the maxillary incisor teeth may be interesting as these are the most prone teeth to root resorption.

Different vibration protocols and different vibration devices should be tested. In the medical field, low magnitude high frequency has been reported to be effective while high magnitude low frequency has not. Although the Acceledent is based on this work, those previously reported vibration protocols were not specifically designed for the oral cavity. This may require a different set of parameters for optimal orthodontic tooth movement and safety.
Likewise, different patients may respond to vibration differently. Older patients and younger patients exhibit different bone quality, bone remodelling patients and biological response to vibration stimulation. What may work for an older patient may not be suitable for a younger patient. Further testing is required to determine which frequency and magnitude provides the most beneficial results.

Compliance in using the device has been an issue. Currently it is recommended for use 20 minutes per day. Testing in the field of duration of use for Acceledent could improve compliance if it is shown that shorter durations of use yield similar benefits.

Nishimura in their rat study hypothesised that vibration could potentially increase vascular flow to areas of compression thereby inhibiting hyalinisation and decreasing root resorption. Histological or vascular studies could be performed to test this theory. Previous studies on root resorption have examined repair of root resorption cavities. If vibration is able to accelerate remodelling of the bony alveolus around a tooth, it could possibly accelerate the repair of root resorption cavities. Histological or micro CT studies could be used to determine if vibration is able to decrease root resorption as well as accelerates healing as well.

In the present study, a statistically significant correlation was made which suggested that patients with initial high levels of root resorption may benefit more from the use of vibration. Genetic testing for root resorption susceptibility may eventually become a possibility and thus the theoretical correlation could be proven or disproven.

The main aim of Acceledent is to increase the rate of orthodontic tooth movement. Future research in the department is needed to assess the efficacy of its claims with a clinical trial. It must be proven that Acceledent works to a clinically significant degree before it can be a widely accepted treatment adjunct.
Acceledent has been advertised to work with all orthodontic appliances including lingual fixed appliances, labial fixed appliances and removable thermoplastic appliances. Clinical studies may be carried out to determine their efficacy is different between the appliances.

Finite element analysis studies of Acceledent vibration may give clues to the potential spread of vibration not just to the teeth but also to the craniofacial skeleton as a whole. This may allow for research into the most effective design of the device.

Vibration in orthodontics is still in its infancy. Initial studies for increasing the rate of tooth movement have been promising. With the introduction of the Acceledent device, the use of vibration in orthodontics could become more widely spread. More clinical trials will be needed to fully access the efficacy of Acceledent as well as its safety.

Daniel Tan