# VIBRATIONS OF HIGH-SPEED DENTAL HANDPIECES MEASURED USING LASER VIBROMETRY

by

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# ABSTRACT

**Objective**: To measure *in vitro* vibration displacement amplitudes of high-speed dental handpieces under unloaded and loaded conditions using a non-contact Scanning Laser Vibrometer (SLV).

**Methods**: Five turbines (two KaVo, three W&H) and two speed-increasing handpieces (one KaVo and one W&H) were investigated using a Polytec SLV (PSV-300). Handpieces were operated under various conditions which included equipping with no rotary cutting instrument (RCI), with a diamond RCI, or with a tungsten carbide bur. Repeated measurements were taken from six selected points on the handpiece. Further tests were performed to study the influence of increasing loads (50 to 200 g) whilst cutting into extracted human teeth. Results were investigated using analysis of variance (ANOVA) at a significance level of $p = 0.05$, and post hoc tests.

**Results**: Maximum handpiece vibrations were less than 4 µm. Significant differences were found between some handpiece models when unloaded. Increasing the load from 100 to 150 g corresponded with an increase in vibration amplitudes. Interactions between RCI type and handpiece model significantly affected vibrations.

**Conclusions**: Variations in displacement amplitudes were observed under different conditions. It was difficult to determine consistent patterns of vibration. Further research is needed in this area.

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# ABBREVIATIONS AND UNITS

| | |
|---|---|
| µm | micrometre (1/1000 metre) |
| ANOVA | Analysis of Variance |
| EDJ | Enamel-Dentine Junction |
| EPSRC | Engineering and Physical Sciences Research Council |
| GN | giganewtons |
| Hz | hertz (cycles per second) |
| ISO | International Organization for Standardization |
| kHz | kilohertz (thousand cycles per second) |
| kPa | kilopascals (thousand pascals) |
| krpm | thousands of revolutions per minute |
| LASER | Light Amplification by Stimulated Emission of Radiation |
| MEMS | Micro-Electro Mechanical Systems |
| MHz | megahertz (million cycles per second) |
| min | minute |
| ml | millilitres |
| MN | meganewtons (million newtons) |
| nm | nanometre (1/1000,000,000 metre) |
| PDL | Periodontal Ligament |
| RCI | Rotary Cutting Instrument |
| rpm | revolutions per minute |
| SI | International System of Units |
| SLV | Scanning Laser Vibrometer |
| SPSS | Statistical Package for the Social Sciences |
| UK | United Kingdom |
| USA | United States of America |

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

A substantial amount of a dentist's time is spent filling teeth or replacing existing restorations[1]. These are procedures which patients often associate with the unpleasant sensations of pain and vibration. It is therefore important to consider the cutting tools that are used to remove diseased tissues and prepare cavities for restoration, and the nature of the vibrations they emit.

The main dental tissues removed in simple restorative procedures are enamel and dentine. The underlying pulp is involved in the reactionary responses to disease and trauma. In an unfavourable oral environment the disease process of caries progressively destroys these tissues. Once operative intervention becomes necessary, restoration usually involves preparation of a cavity using cutting instruments, in readiness for placement of a filling material.

Various apparatus has been used for gaining access to caries and for removal of diseased tissue, but using rotary handpieces and their associated instruments remains the most common method[2]. The development of these tools underwent significant change in the 1950s, when high speeds of instrument rotation became possible[3]. There have been continued improvements in the design of these devices over the subsequent years, and various means of testing efficiency have been introduced.

Use of rotary instruments can lead to the production of heat[4, 5], cracking of enamel[6, 7], and deposition of debris on the cut surfaces[8]. There are possible implications for the long-term health of the operator in terms of auditory damage[9] and the effects of vibrations on the upper limbs[10]. Patient perceptions of handpiece vibrations are associated with pain[11]. The equipment can also become damaged through repeated use[12, 13].

Understanding the physical characteristics of these tools under a variety of conditions can help to identify potential problems and lead to improvements in design. Measurements of handpiece vibration in the past have been hindered by a lack of appropriate technology. However laser vibrometry has been introduced into many different areas of engineering and shows great potential for assessing the vibrations of dental handpieces.

## 1.2 Aims

This study aims to provide a better understanding of the vibrations of high-speed dental handpieces using laser vibrometry. Various operating conditions were investigated *in vitro*, including the effects of handpiece model, instrument type and load.

## 1.3 Objectives

The objectives of this research were to:

- compare measured maximum cutting instrument rotation rate with the approximate maximum rates documented in handpiece manufacturers' literature.
- determine the ability of a scanning laser vibrometer to measure vibrations of dental handpieces.

- measure unloaded vibration displacement amplitudes of high-speed dental turbines and speed-increasing handpieces when equipped with, and without, cutting instruments.
- compare vibration data acquired at different scan point positions across the surfaces of handpieces.
- establish whether handpiece model affects vibrations detected at the turbine head whilst loaded.
- assess the effect of increasing load upon displacement amplitudes of turbines.
- determine whether type of cutting instrument affects vibrations of turbines.
- evaluate the consistency of handpiece vibration results achieved using identical cutting instruments.
- determine the influence of exchanging teeth upon the magnitude of loaded handpiece vibrations.

# CHAPTER 2

# ANATOMY AND HISTOLOGY

## 2.1 Introduction

In order to comprehend the manner in which dental handpieces are used to cut cavities in teeth, it is helpful to first understand the structure of the dental tissues. There are a number of clinical conditions that are treated operatively using dental handpieces; much of the information provided here is relevant to understanding these problems or disease processes. Particular emphasis is also placed on factors related to the action of dental handpieces, such as vibration detection or crack formation, which will be explained further in subsequent chapters.

The mineralised tissues that make up the teeth are enamel, dentine, and cementum (Figure 2.1). Enamel covers the outer layer of the tooth crown, whereas cementum forms the outer layer of the root. Beneath each of these is found dentine. This forms the bulk of the tooth and encloses the dental pulp, which is the innermost tissue of a tooth. The tooth itself is held in place by the surrounding periodontal tissues including the periodontal ligament, gingiva (gum) and alveolar bone.

## 2.2 Enamel

As the outermost layer of a tooth crown, enamel is the hardest tissue in the human body[14]. The thickness varies from a very thin layer where it meets the cementum, up to around 2.5 mm thick over the biting surface[15]. Its structure allows it to withstand shearing stresses and impact forces well as it has a high modulus of elasticity[15], although its brittle nature makes it

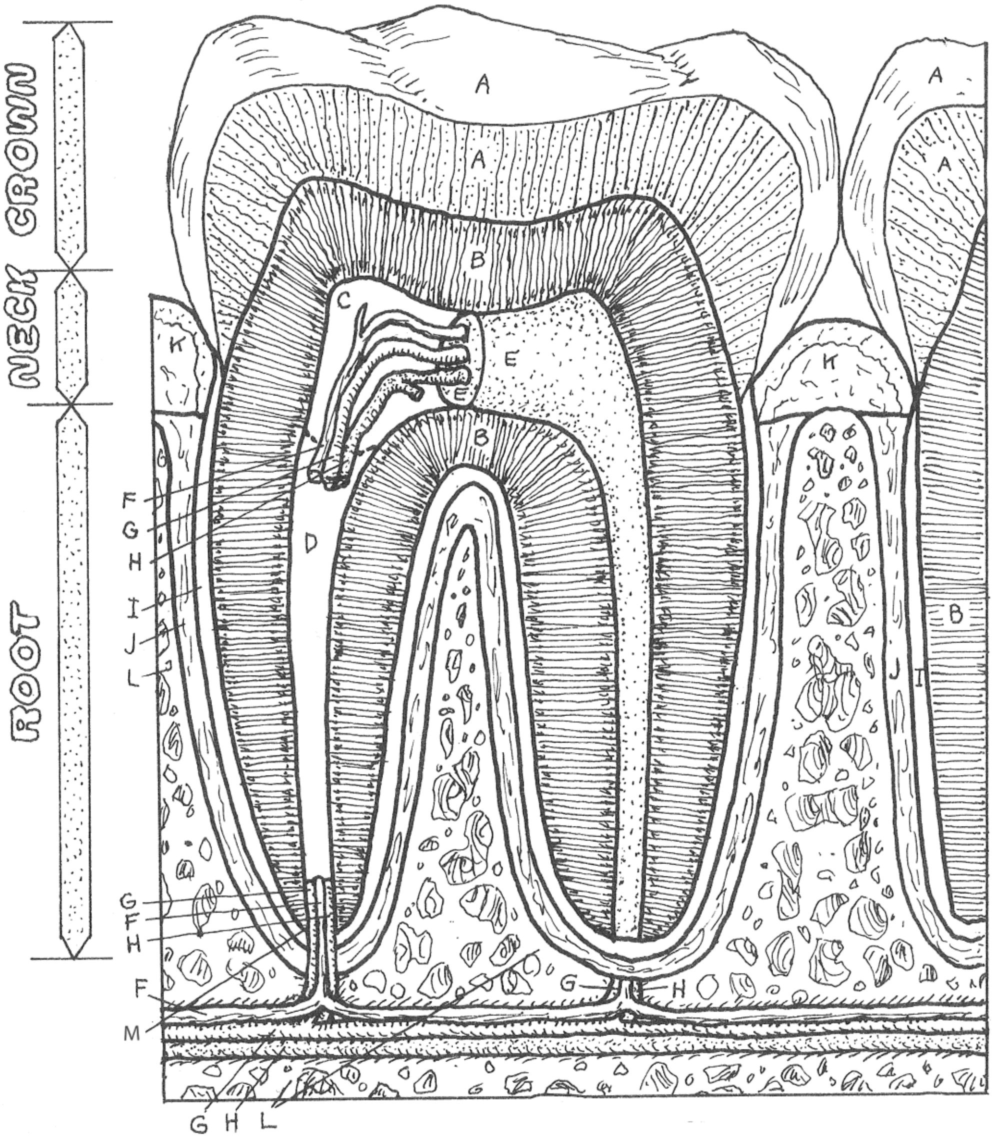

Figure 2.1: The anatomy of a typical molar tooth. Adapted from Kapit and Elson[16].

<u>Key to Figure 2.1</u>:

| | |
|---|---|
| A – Enamel | H – Vein |
| B – Dentine | I – Cementum |
| C – Pulp cavity | J – Periodontal ligament |
| D – Root canal | K – Gingiva |
| E – Pulp | L – Alveolar bone |
| F – Nerve | M – Apical (root) foramen |
| G – Artery | |

susceptible to fracture in areas not supported by underlying dentine[17]. It also exhibits some permeability, allowing exchange of some fluids, bacteria and bacterial products. This permeability decreases with age[17]. Enamel is non-vital and insensitive; once it is laid down it is not possible to replace or regenerate lost tissue[15, 17]. The physical properties of enamel are compared with those of dentine in Table 2.1.

Enamel is highly mineralised and acellular, with around 96% inorganic material in the form of calcium hydroxyapatite crystallites[17]. The crystallites have an irregular outline that sometimes appears hexagonal in cross-section. They are approximately 60-70 nm wide and 25-30 nm thick, and may be long enough to extend from the enamel-dentine junction (EDJ) to the tooth surface[17]. The remaining 4% of enamel consists of water and an organic matrix of amino acids, proteins and lipids[17]. The hardness of enamel is related to both the hardness of the crystals and the strong adhesion between crystals[18].

The densely packed hydroxyapatite crystals in mature enamel have a regular structural arrangement. These structures are called prisms or rods, and each is approximately 6 µm wide[19]. The structural arrangement of enamel differs in appearance depending on the orientation of the prisms within the section, and it is impossible to view a whole prism in a two-dimensional section[20]. Under the scanning electron microscope these prisms can appear as striations extending from the EDJ to the surface, following a sinuous course[17]. Each prism is surrounded by an interprismatic enamel sheath, which has a higher organic content than the prism[21].

Table 2.1: A comparison of the physical properties of enamel and dentine. From Berkovitz *et al.*[15]

| | Enamel | Dentine |
|---|---|---|
| Specific gravity | 2.9 | 2.14 |
| Hardness (Knoop no.) | 296 | 64 |
| Stiffness (Young's modulus) | 131 GN $m^{-2}$ | 12 GN $m^{-2}$ |
| Compressive strength | 76 MN $m^{-2}$ | 262 MN $m^{-2}$ |
| Tensile strength | 46 MN $m^{-2}$ | 33 MN $m^{-2}$ |

GN = giganewtons (N x $10^9$), MN = meganewtons (N x $10^6$)

A number of other phenomena such as tufts and lamellae can be observed in dental enamel after the application of various investigative techniques. Enamel tufts are branched areas of hypomineralisation adjacent to the EDJ, and extending for a short distance into the enamel. Situated between groups of prisms, the spaces are filled with protein[17]. They may be of clinical relevance in the spread of bacteria at this junction in teeth affected by the disease process of caries. Enamel lamellae are defects that extend from the surface to various depths, sometimes running through the whole thickness of enamel. They can appear as cracks on the surface, but differ in that they are filled with organic material[17]. They may be another potential route for the progression of caries, and also a feature along which cracks may be propagated[22].

## 2.3 The dentine-pulp complex

Unlike enamel, dentine is a vital tissue and is capable of repair. Dentine forms the bulk of a tooth, lying between the enamel and pulp of the crown, and the cementum and pulp of the root. The border between enamel and dentine, the enamel-dentine junction (EDJ, or amelo-dentinal junction) has a scalloped appearance, which is thought to improve adherence between the two tissue types, and acts as a soft cushion between them[23]. Dentine (a hard tissue) has a close relationship with pulp (a soft tissue), forming an inter-dependent complex[17]. In fact the cell bodies of odontoblasts (the cells responsible for the production and maintenance of dentine) lie within the outer layer of the pulp, whilst their cytoplasmic extensions are enclosed within the dentine[24]. The soft dental pulp containing blood vessels and nerve bundles is found in the centre of a tooth, enclosed by the dentine. The space it occupies in the tooth crown is called the pulp chamber, and the pulp also extends internally within the root canals[17].

Dentine is less mineralised than enamel, although it is harder than bone and cementum (Table 2.1). Its composition is approximately 50% inorganic, 30% organic and 20% water (by volume) in mature teeth[23]. Most of the mineral component is hydroxyapatite, and although the crystals are similar to those found in enamel, they are much smaller[25]. The organic matrix comprises mainly type I collagen fibres held within an amorphous ground substance containing proteins, growth factors and lipids. As dentine has some elasticity, it helps to prevent shattering of the overlying brittle enamel[23]. The extent of mineralisation of the tissue is responsible for these mechanical properties in healthy teeth, whilst destructive disease processes can result in softened dentine[26].

The main feature of dentine is its tubules, which are formed by odontoblasts and sometimes contain odontoblast processes. The tubules run between the EDJ and the pulp with a roughly sigmoid-shaped primary curvature[17]. Near the pulp these have a diameter of approximately 2.5 µm, but they are tapered in shape and so the diameter at the EDJ measures around 900 nm[17], accompanied by more intertubular dentine[27]. There are interconnecting branches, increasing the permeability of the tissue, and occasional blind-ended offshoots.

### 2.3.1 Sensitivity and innervation of dentine

During cavity preparation, exposure of dentine can cause discomfort to patients, and local anaesthesia is often used to alleviate this pain[28]. Stimuli include cold water, drying of the dentine surface or contact with dental instruments[17]. Various models have been proposed for the mechanism of dentine sensitivity, but the most likely seems to be the hydrodynamic hypothesis[29, 30] as described by Brännström and Åström[31]. This proposes that the movement of fluid within the tubules elicits pain in response to thermal, mechanical, osmotic and evaporative stimuli[24, 32, 33]. Other theories are that pain is detected directly by nerve endings within the dentine, or that the mechano-sensitive membrane of an odontoblast process triggers an electrophysiological signal. This is thought to be similar to the way in which an action potential is propagated along nerve axons[34, 35].

There are many types of nerve fibres innervating the teeth. They enter with the blood vessels through the apical foramen at the end of the root. Nerves supplying the pulp are either sympathetic or sensory, although there is a possibility that some parasympathetic innervation also exists[36]. The sensory fibres can be categorised physiologically according to stimulation intensity and speed of conduction. The three main sensations associated with them are described as a poorly defined ‘pre-pain’, a sharp pain, or a dull ache[37]. Some evidence of nociceptive and non-nociceptive mechanosensitivity has also been found, though not in all sensory neurons[35, 37]. Some free nerve terminals penetrate a short distance into the dentine of mature teeth, probably under the influence of specific guidance proteins and nerve growth factors[4, 6, 7]. These nerve endings lie alongside odontoblastic processes in up to 70% of inner crown dentine[38], and it is thought that there may be some communication between them[39, 40].

## 2.4 Periodontium

The tissues surrounding and supporting the teeth are described collectively as the periodontium. These include the cementum (the mineralised tissue covering the root), gingivae (gums), periodontal ligament and the bone of the socket, known as alveolar bone[41]. In a healthy mouth these structures function as a unit and hold the tooth in place, whilst allowing a limited degree of movement[42]. Increased mobility of a tooth can be an indicator of periodontal disease[43]. The periodontal ligament (PDL) is a specialised dense fibrous connective tissue that separates the outer layer of the tooth root (cementum) from the inner layer of the tooth socket (alveolar bone)[44], providing a cushioning support to dissipate biting pressures averaging around 10 kg[45].

### 2.4.1 Mechanoreception and vibration perception

The movements of teeth within their sockets are detected by mechanoreceptors in the PDL. These receptors are capable of communicating detailed information about the speed, amplitude, direction and duration of displacement of individual teeth to the brain[45, 46]. This produces a response that influences the jaw movements during chewing[15]. The mechanoreceptors are highly sensitive to changes in pressure of less than 1 N[46]. Other sensory nerve endings within the PDL are nociceptors, which detect pain[45], and sympathetic free nerve endings thought to affect the blood flow to the area[17].

Vibratory stimuli have been found to have a conditioning effect upon mechanoreceptors, by temporarily increasing the acute response to mechanical stimuli, depending upon frequency and duration of vibration[47], but perception of vibration is not necessarily considered painful[48]. Thresholds for perception of vibratory stimulation of teeth vary between individuals, but in general a linear increase in threshold (force) occurs between frequencies of 40 and 315 Hz for central incisors[49].

Sensations are not only distinguished within the PDL. Some mechanoreceptors are found within the tooth pulp[50]. Forces applied to teeth can also be detected by nerve endings in the gingiva or periosteum (the outer layer of bone)[45]. Vibrations applied to teeth can pass through bone and be detected in the inner ear and jaw muscle spindles[51].

# CHAPTER 3

# DISEASES AND DAMAGE OF TEETH

## 3.1 Introduction

When teeth are damaged through trauma or disease, a patient will often require dental treatment. In order to manage each case, it is important that clinicians understand the nature of the problem and any underlying disease processes[28]. Some of the most common reasons for destruction of dental tissues are described in the following paragraphs, but issues relating to treatment are covered in Chapter 4.

## 3.2 Caries

The most common cause of tooth damage is caries[52]. Caries is a chronic disease where progressive destruction of dental hard tissues (enamel, dentine and cementum) occurs under the influence of bacteria and their products when exposed to dietary carbohydrates. The process involves demineralisation of the inorganic material followed by disintegration of the organic component. It relies on there being an available tooth surface, an appropriate substrate (ie fermentable carbohydrate), microorganisms (plaque bacteria), and sufficient time[53]. This relationship is conventionally illustrated using a Venn diagram (Figure 3.1). Caries can potentially result in pain, the formation of cavities and eventual tooth loss.

Each exposure to dietary carbohydrates will produce an effect, so that regular consumption will mean that the destructive cariogenic conditions are maintained for longer periods[54]. Fortunately, under appropriate conditions it is also possible to arrest the progression of caries, and even for some remineralisation to occur if cavitation has not yet occurred[55, 56].

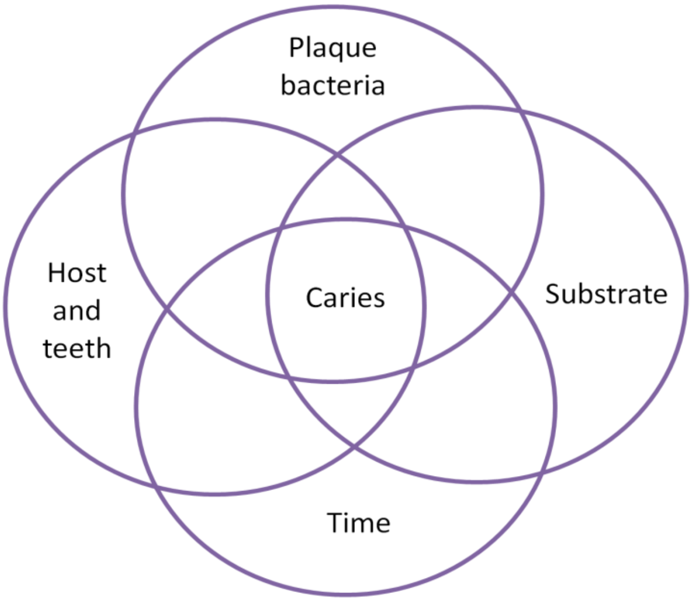

Figure 3.1: Factors which must coincide for the existence of caries. Substrate refers to a suitable fermentable carbohydrate being present in the diet. Adapted from Samaranayake[57].

Saliva is supersaturated with calcium and phosphate ions, which can replenish those minerals lost, particularly in the presence of fluoride. The destruction of the dental hard tissues can therefore take months or years to progress, due to the cyclical nature of periods of destruction and repair[55].

### 3.2.1 The carious process

The carious process is first evidenced macroscopically on the tooth crown as a white spot lesion on a susceptible enamel surface, which is due to an increase in porosity caused by acids produced by plaque bacteria[1]. The most common locations for the disease to manifest are in areas that are difficult to access, where plaque is accumulates and is retained, such as within the depths of a fissure[58]. Caries can also be initiated in the root cementum, or directly into dentine where the thin cementum has already been worn away[56].

In a typical lesion cariogenic bacteria and their products progress through the enamel. Upon reaching the EDJ, a lateral spread of the lesion occurs, undermining the enamel[56]. The rate of destruction of dentine is variable, and there is still the possibility that progression can be prevented if enamel cavitation has not yet occurred[1]. When conditions repeatedly favour demineralisation and the area of affected dentine increases, the overlying sound enamel becomes vulnerable to fracture and cavitation, particularly under masticatory stresses. Once the surface enamel collapses and plaque becomes trapped within the cavity, further progression of the caries is likely and some form of restoration will usually be required[59].

At this stage the patient is liable to experience some pain due to the sensitivity of dentine and its intimate relationship with the pulp, although it is not inevitable. Some protection is afforded by the defence mechanisms of the pulp-dentine complex, such as the deposition of tertiary dentine or sclerosis of tubules[60]. Pulpal inflammation (pulpitis) may occur chronically under prolonged provocation, or as an acute reaction to a sudden stimulus. Acute inflammation is usually accompanied by pain, which is triggered by hot, cold, or sweet stimuli[1]. Where the damage is great or infection uncontrolled, the repair mechanism is compromised and the pulpitis becomes irreversible[37]. Swelling of the pulp due to dilation of blood vessels is restricted by the physical constraints of the surrounding hard tissues, and necrosis can occur. Necrotic pulps are painless as there are no viable nerves to transmit pain[1]. But once the tooth loses its vitality, the inflammation can spread into the supporting periodontal tissues[61], causing considerable discomfort.

## 3.3 Trauma, wear, and developmental defects

Rather than undergoing the relatively slow process of carious disease, traumatic damage to teeth can happen suddenly, for example due to sports injuries or vehicular accidents. If a tooth crown is fractured, the defect may involve enamel only, enamel and dentine, or enamel, dentine, and pulp. The fracture may be complete (with visible separation of segments) or incomplete, otherwise known as 'cracked tooth'[52]. Fractures that extend into dentine can expose a large number of dentinal tubules, providing bacteria with a route to the pulp[62]. Depending on the type of injury other structures in the mouth may have been damaged (eg blood vessels), and it is possible that the tooth may have lost its vitality[28].

Loss of dental hard tissues from tooth surfaces can occur as a result of wear through erosion, attrition or abrasion. Erosion occurs by chemical means, by exposure to an acidic diet or regurgitated stomach acid. Attrition is caused by physical contact with opposing teeth. Abrasion is the mechanical wearing of teeth by other substances such as abrasive toothpastes or hard toothbrushes. One factor thought to predispose a tooth to surface loss is that bending stresses cause disruption in the enamel in the cervical area of a tooth (where the enamel of the crown meets the cementum of the root) causing 'abfractions'[52]. All types of wear are irreversible[28].

Problems can also occur with teeth during their development, resulting in malformed, discoloured or missing teeth. The aetiology is varied and not always easy to establish, and can be due to both local and systemic insults[63] or hereditary conditions[64]. Conditions such as enamel hypomineralisation can lead to increased sensitivity, extensive microcracking and susceptibility to fracture[65]. If drugs such as tetracyclines have been administered during calcification of teeth, the teeth may become extensively discoloured as a side-effect, and the aesthetics of this can cause considerable concern for patients[66].

# CHAPTER 4

# REPAIR AND RESTORATION

## 4.1 Introduction

Teeth are capable of a certain amount of natural repair in response to disease or trauma. Under favourable conditions, this potential can be exploited by patients and dentists to conserve as much healthy tissue as possible and encourage recovery of tissues without significant intervention[67]. However operative treatment may at times be necessary in order to restore a tooth[55]. It should be noted that not all restorations are carried out to replace tissue lost through caries; other reasons include trauma, wear, and developmental defects[28]. The replacement of failed restorations is also a very common occurrence[55].

### 4.1.1 Natural repair

Natural repair mechanisms of teeth act to protect the pulp from exposure to bacteria[68], and the dental tissues vary in their reaction to insult. Once lost, enamel cannot be replaced as it is a non-vital tissue. However a certain degree of remineralisation can occur through an exchange of calcium and phosphate ions within a favourable oral environment[56]. Fluoride can also aid in the strengthening of enamel[17].

Dentine on the other hand is capable of repair, and responds in different ways depending on the stimulus. Primary and secondary dentine occur naturally in health, but tertiary dentine forms only in response to insults such as caries or restorative procedures[60]. Primary dentine is that which is established during initial development, and forms the main bulk of dentine. Secondary dentine is laid down more slowly once the tooth root is fully formed, and its continued deposition with increasing age helps to protect the pulp from exposure (eg whilst cavities are prepared for restoration)[17]. Tertiary dentine is also known as reactionary dentine (a deposition of material that occludes tubules when a mild injury such as slowly-progressing caries occurs) or reparative dentine (a rapid response to more severe injury such as tooth fracture or deep cavity preparation by cell proliferation and scar tissue formation)[62, 68].

Whenever the pulp is damaged an immune response occurs in the form of inflammation (pulpitis), which can sometimes resolve without loss of tooth vitality[17]. If infection is removed from the area, periodontal tissues are capable of complete healing, but pulp and dentine do not return to their original state once the natural repair mechanisms are complete[37].

### 4.1.2 Restoration of carious teeth

Management of caries should initially take advantage of the possibility of remineralisation of enamel through preventative treatment[56], but where the destruction of the tissues has progressed further, operative intervention may become a necessity. Teeth damaged by caries are restored in order to remove the diseased tissue and prevent further spread, re-establish function, facilitate control of plaque, reduce sensitivity, preserve pulp vitality and improve aesthetics[1, 55]. Enamel and dentine are removed, then replaced with a restorative material that forms a protective seal between the dentine-pulp complex and the external environment[17].

Historically, restoration of teeth involved an attempt to remove all infected tissue and also required some destruction of sound tissue before placement of a restorative material. Described as one of the pioneers of modern dentistry[69], G. V. Black is well recognised for his proposal in 1908 of the 'extension for prevention' concept[67, 70]. This involved positioning the margins of a cavity using standard outline profiles in order to achieve retention, resistance and convenience forms[71].

These principles have now been extensively modified due to a better understanding of caries, and technological advancements leading to new materials and improved restorative procedures in recent years[28]. There has been a significant progression in accepting the importance of preserving as much natural tissue as possible[67]. The focus has shifted towards preventive measures: promoting health through education of patients and the implementation of public health campaigns[72]. The consequent decline in the rate of dental caries has been reported in the literature[72-74].

However, these changes over the last century have not yet negated the need for operative intervention in the treatment of carious lesions. With this in mind, a ‘minimally invasive’ attitude is becoming increasingly adopted by the dental profession[55]. Some of the factors that have influenced the current approach to cavity preparation include better understanding of the mechanisms of the carious process, improved methods for early detection and monitoring of the disease, advancements in restorative materials and technological developments in handpiece design[55, 75]. These allow more conservation of the natural tissues than was possible in the 'extension for prevention' era[52], although evaluating how much demineralised dentine is infected and should be removed can be challenging, and is usually decided by a subjective assessment of the consistency of the tissue[76].

### 4.1.3 Restoration following trauma, wear or developmental defects

Fractures resulting from trauma to the crown of a tooth sometimes only extend into the enamel, and would not necessarily require operative treatment. However if a fracture has caused an exposure of the dentine or pulp, immediate intervention is usually indicated[28]. If tooth vitality has been lost, the pulp is removed and the root canals filled to prevent infection and discoloration[28].

In contrast, tooth wear is generally managed by prevention and monitoring, but occasionally the placing of a restoration may be worthwhile in order to reduce sensitivity, improve appearance or prevent further deterioration[28]. Severe loss of tooth surface can lead to infection in non-vital teeth, also necessitating treatment. Other reasons for restoring worn teeth are to combat temporomandibular joint disorders or problems with phonation (speech)[52].

Developmental defects often do not require treatment, and can sometimes be improved using only minor interventions such as bleaching or applying fluoride, whereas some necessitate operative treatment to prepare teeth for veneers or crowns[77]. Staining caused by a side-effect of drugs such as the antibiotic tetracycline cannot be removed, and bleaching is usually only partially successful[66]. However it can be successfully treated operatively in order to improve aesthetics. First the tooth crown is slightly reduced using rotary cutting instruments in a dental handpiece. Then composite resins or porcelain veneers are applied, covering over the visible portion of the tooth[66, 78].

## 4.2 Cutting

When dental enamel is cut, there are in fact two mechanisms by which the tissue is removed – plastic deformation and fracture. In plastic deformation, a chip of enamel is removed at the cutting edge of the tool and produces a 'smear' layer of debris. Fracture (or shattering) occurs a little way ahead of the cutting edge and cleaves the enamel along natural planes, such as those that exist between enamel prisms[79]. In this section, the mechanisms of cutting in dentistry are compared to industrial cutting. In addition, having already described the rationale behind common dental restorative procedures, consideration is given to some of the specialised forms of cutting used in dentistry.

### 4.2.1 Industrial cutting

An understanding of cutting mechanisms such as fracturing and plastic deformation is important to the manufacturing industry. Cutting by exploiting natural lines of weakness can be seen when sedimentary rock fractures along its grain boundaries under the influence of diamond stone-cutting tools[80]. An example of plastic deformation is when material is removed from a metal to create a workpiece of desired specifications[81].

The type of industrial cutting that relates most closely to the action of a dental rotary cutting instrument is drilling, whereby cylindrical holes are created by a 'twist drill' with helical flutes. Machining conditions can be precisely controlled (increasingly by computers)[82]; the substrate can be selected and its composition manipulated according to purpose[83], and input parameters can be quantified. Therefore it is possible to construct models to predict the output in terms of cutting forces, chip behaviour, temperature distribution at the cutting edge and tool wear rates[84], and for repeated processes to create identical products of exact dimensions. Although similar principles could be applied to dental cutting, the outcome is far less predictable due collectively to the composite nature of dental tissues, the hand-held manipulation of complex cutting tools by different operators and the difficulty in controlling numerous environmental parameters.

### 4.2.2 Endodontics

One form of specialised dental cutting occurs when dentine is removed from inside root canals during a course of endodontic treatment. Where infection has progressed so far through the tooth that the vitality of the tooth is endangered, or when trauma occurs and the blood supply to the tooth is damaged, it may be necessary to remove the pulp[1]. The empty pulp chamber and canals are prepared then sealed with an inert material (root canal filling).

Cutting of dental tissues in preparation for filling of root canals includes creating an access cavity (in much the same way as for a conventional filling), followed by cleaning and shaping of the canal using specialised endodontic instruments[52]. These hand instruments are known as files, reamers or broaches. The same purpose can be achieved using specially designed flexible nickel-titanium files inserted into slow-speed rotary handpieces, but occasional breakages are an unfortunate weakness of these instruments[85], and files differ in their effectiveness depending upon variations in cutting blade design[86]. These handpieces can be driven by either air or electric motors, but no significant difference in file breakages was found between motor types[87]. The root canal can also be shaped using laser ablation[88]. Sonic or ultrasonic (endosonic) oscillating units with attached files are sometimes used for canal debridement and have been evaluated for cutting efficiency[89] but have not been found to be very effective as tools for shaping root canals[52].

### 4.2.3 Implants

In restorative dentistry, dentine and enamel are not the only hard tissues that are removed; bone is also cut in preparation for placement of implants. Implants have been used to replace missing teeth since the early 1980s[52]. They are metal posts (usually titanium) that are either screwed or tapped into the alveolar bone of the upper or lower jaw as a surgical procedure, and support replacement teeth in the form of crowns, bridges or dentures. The socket into which an implant is introduced must be carefully drilled in a precise location. Specialised slow-speed rotary handpieces and instruments have been designed for this purpose[52].

## 4.3 Tools for tooth preparation

With conservative dentistry in mind, important considerations in the design of a cutting instrument will relate to establishing a balance between efficiency and minimising trauma[71].

Banerjee *et al.*[76] describe an ideal cutting instrument as:

- comfortable and easy to use in the clinical environment
- able to discriminate and remove only diseased tissue
- painless, silent and requiring only minimal pressure for optimal use
- not generating vibration or heat during periods of operation
- affordable and easy to maintain.

### 4.3.1 Hand instruments

In the eighteenth and nineteenth centuries caries was removed by scraping with hand-held instruments or by cauterising[70]. So-called ‘enamel cutters’ were used to gain access to the carious dentine, which was then removed using excavators[90]. Using such hand instruments was laborious and time-consuming. As other means of removing the bulk of the enamel developed, the design of hand instruments evolved[71].

Hand instruments used to cut teeth and remove caries remain in employment today, and include excavators, chisels, hatchets and hoes. Excavators, with a disc- or pear-shaped cutting blade are mainly used for removal of carious dentine[91]. Chisels, hatchets and hoes aid in the preparation of cavity margins by cleaving enamel, such as that which is unsupported[79], and by smoothing the cavity floor and walls[92]. These cutting instruments are made of stainless steel or carbon steel, and can be of use in areas that are not easily accessed by rotary instruments[28].

In a comparison of methods of caries excavation, hand instruments were found to be the most efficient and effective in terms of time taken and material removed[93]. A microscopic examination of the effect of cutting enamel using a hand-held chisel corresponded with erratic cracking away from the site of impact, but a direct observation of this interaction proved difficult to accomplish[22]. Hand instruments are cheaper than rotary handpieces, easier to clean and sterilise, and can be used in parts of the world without a reliable electricity supply[94].

### 4.3.2 Rotary instruments

Despite the availability of alternative techniques, most removal of dental tissue is still performed using rotary cutting instruments (RCIs)[2, 75, 95] and this is expected to continue for the foreseeable future[6, 96]. As more adults retain their teeth for longer and life expectancy improves, the need for reparative dentistry will remain[74]. Some minimally-invasive techniques, such as a 'tunnel preparation' still require the use of high-speed handpieces with small RCIs[55]. But it is in the removal of larger quantities of tissues (eg when cutting a crown preparation), or of existing heavy metal restorations, that alternatives to the rotary handpiece fall short[2, 97].

Because of the importance of rotary cutting instruments in clinical practice, and as high-speed handpieces form the basis for this research project, Chapter 5 is devoted to the developmental history, design features, physical characteristics and biological effects of dental handpieces.

### 4.3.3 Air abrasion and air polishing

An air/powder abrasive system was developed by R V Black in 1945[3]. Particles, suspended in a narrow stream of air and directed toward a tooth, abrade the surface by transfer of kinetic energy[55]. Various abrasives have been employed, but aluminium oxide is the standard choice[76]. The coarseness of the surface finish depends on the hardness and size of abrasive particle[76].

After the introduction of high-speed turbine in the 1950s the airbrasive technique declined in popularity, but regained interest in the mid 1990s[98]. It has advantages over rotary drilling such as reduced noise, heat, bone-conducted vibration and other mechanical stimulation[28, 55, 76, 99]. Patients have reported less sensitivity, although not consistently[55]. The cavities produced through the use of this technique have rounded contours, which reduces internal stresses and may increase the longevity of the eventual restoration[55], although a similar effect could be achieved with a large diameter round bur.

There are also a number of disadvantages to using air abrasion, such as dust pollution (impairing visibility of the operative area and potentially causing harm by inhalation), and a lack of tactile sensation for the operator[76]. The demarcation between infected dentine (requiring removal) and relatively healthy dentine (which should be preserved) is largely discerned by sensing the change in hardness[100]. Without this feedback mechanism there may be either insufficient removal of infected tissue (hence jeopardising the success of the restoration), or conversely over-extension of the cavity margins and loss of sound tissue[76].

Air abrasion is particularly useful for removal of dental plaque or stains[3] or for creating minimal cavities[55, 76, 96]. However, through recent developments in micro-abrasion technology, it is hoped that a system may be developed which could differentially remove softened diseased tissue only[28]. Advancements in dust protection and removal may lessen the dangers of inhalation for both patient and dentist[76].

Banerjee *et al.*[76] describe air-polishing, which is similar to air-abrasion but differs in that the particles (sodium bicarbonate and tricalcium phosphate) are water-soluble. The particles are carried in a jet of water that is propelled by air pressure, with the advantage that the abrasive is not released beyond the immediate area of operation. As with air-abrasion, this technique carries the risk that sound tissue will be removed due to its non-selective nature[76].

### 4.3.4 Ultrasonic cutting and sonoabrasion

It was in the 1950s that there was the most interest in cutting teeth by ultrasonic means, when Nielsen *et al.*[101, 102] carried out a number of investigations. The cutting action was due to high frequency (25 kHz) mechanical vibrations generated by a magnetostrictive or piezoelectric transducer, and enhanced by bathing the tip in an abrasive slurry.

Unfortunately the inconsistent results meant that the studies were abandoned, despite positive feedback from patients in a clinical trial who appreciated that there was less vibration than when a rotary handpiece was used[76].

Although ultrasonic cutting instruments were not successfully introduced for restorative procedures, sonic air-scalers have been effectively modified to be used for cavity preparation in the guise of ‘sonoabrasion’. Kinetic energy removes tissues through high frequency oscillations of a diamond-coated tip, which is powered by an air-driven handpiece[99]. Sono-abrasion is useful in the preparation of minimally invasive cavities[99], finishing cavity margins, and may be able to remove softened, carious dentine[76]. It is also less damaging to adjacent teeth than rotary methods of cavity preparation, but is likely to produce some heat locally[99].

The prospect of cutting bone by ultrasonic means has been established within the context of maxillofacial surgery, with particular emphasis on the precise nature of the procedure[103-105]. Additional investigations in this field are anticipated[103-105].

### 4.3.5 Lasers

Laser is an acronym for Light Amplification by the Stimulated Emission of Radiation. In dentistry lasers have been used for a numerous purposes. Amongst other uses they are utilised in the detection of caries[106]; to kill bacteria in dentine by light activation of bactericidal agents[107]; and to increase resistance of enamel to demineralisation[108]. Their potential in cutting hard tissues has been under investigation since 1963 (shortly after the first laser was constructed)[109]. They continue to be commonly used for this purpose, but have advanced significantly[110]. Studies have shown that cavity preparation and removal of caries can be achieved using a variety of types of laser[76, 111], that they produce less vibration during cutting than rotary instruments[112, 113], and that they are well tolerated by patients[114]. The cutting mechanism is due to the absorption of light into water within the dental tissues. The irradiated water suddenly evaporates, resulting in ablation of the surrounding area[88].

In the past many of these lasers were considered expensive[96], bulky, difficult to control, and responsible for thermal damage to the pulp[76]. However, rapid advances in the field are resulting in new technologies being applied in the quest for a more practical laser-powered system, including the possibility of increased selectivity of tissue type[76, 107, 115], and avoidance of enamel cracking[111, 116]. The $CO_2$ laser shows potential as a relatively inexpensive tool for removal of hard tissues without adverse effects if optimal settings are used, but further research is needed to evaluate its performance under more specific conditions[107, 117]. Since the first attempts to remove dental hard tissues using lasers there has been speculation about whether they can be a suitable alternative to rotary handpieces[109, 114, 118, 119], but drawbacks still exist[120-122] and their value remains limited as they are unsuitable for procedures requiring bulk removal of tissue or toxic heavy metals[2].

### 4.3.6 Chemicals, enzymes and plasma

The main systems used for chemo-mechanical removal of carious dentine have been Caridex, introduced in the late 1970s, and the more recent Carisolv gel. Upon application of the chemical, dentine is softened so that it can be removed with specially designed hand instruments[76]. One benefit is that patients report significantly less pain than conventional methods such as rotary handpieces and hand instruments[123]. The main drawback is that these systems still require the use of conventional rotary methods for gaining initial access to the carious lesion[76].

The concept of employing enzymes for the removal of carious dentine arose as a result of a growing understanding of the carious process in the early 1980s[75]. There are reports that this has been accomplished in the research setting, but confirmation that this is a viable technique for adoption in the clinical setting has not yet been forthcoming[75, 76].

# CHAPTER 5

# ROTARY INSTRUMENTATION

## 5.1 Introduction

Rotary handpieces are very important tools in dentistry, as they provide the main means for removing hard tissues in restorative treatments[2]. This chapter gives consideration to key advancements in the history of their development, before summarising the types of handpieces and cutting instruments currently in use in dental practices. Information is provided about testing of physical characteristics (such as vibration measurement). Also included are descriptions of some of the biological effects of handpiece use on the dental tissues, the patient and the operator.

## 5.2 History of rotary instrumentation

The first attempts to use cutting instruments in a rotary manner occurred in the 18th century[6, 95]. Various systems were devised to facilitate the twisting of burs, such as the finger ring of 1846[71, 90]. However the first successful driven handpiece arrived in the 1870s with the introduction of the foot treadle engine by the American dentist, James Beall Morrison[69, 70, 95]. This remained popular for a number of years; despite early electric motors being introduced in 1864, they were not widely used until the 1950s[75]. The flexible cable used connect the handpiece to the foot treadle or electric motor was replaced by the endless cord arm in 1911, enabling a smoother transmission of power[69]. Straight and contra-angled handpieces were available at the time, and there was little change in their design until the middle of the 20th century[90, 95].

Although the benefits of high speeds of instrument rotation had been recognised by Emil Huet as early as 1911[95], and Walsh had demonstrated in the 1940s that vibrations would not be perceived at high frequencies[2, 124], a number of obstacles had yet to be overcome. Handpiece bearings were unable to withstand the pressures generated at speeds over 20 krpm[90, 95]. A mechanism for counteracting the frictional heat generated by cutting was also necessary[90]. Moreover, the cumbersome cord arm drive required the dentist to remain standing[90].

Many of these much-needed developments finally arrived in the 1950s, such as the availability from 1955 of an effective cooling system that involved an air and water spray mechanism fitted to the handpieces[90, 95], which allowed for development of higher speeds in cutting[75]. The same decade witnessed advancements in other types of dental cutting instruments such as air abrasion and ultrasonic handpieces[96].

### 5.2.1 The high-speed era

Arguably the most revolutionary advancement in the design of dental handpieces occurred in 1957, with the establishment of Borden's 'Airotor' as the first commercially viable high-speed handpiece driven by an air turbine in the head[3]. There were many other contributions to the pursuit of high-speed dentistry including the Page-Chayes belt-driven handpiece[3, 96], Norlen's 'Dentalair' turbine[90, 95, 96], and hydraulic turbines such as the Turbo-jet[90, 96, 124]. However the Airotor's miniature ball bearings, small instrument shaft diameter, and lubrication system, all of which combined to allow speeds of up to 300 krpm, earned it recognition as the handpiece of the future[90, 96].

The 1970s saw the advent of KaVo’s Super-Torque turbine with rubber-mounted bearing races, and later developments led to dynamically-balanced rotors. These designs all carried the advantages of reduced vibration and, since bearing wear was reduced, increased longevity[125]. One of the limitations of turbine design however is its low torque, which can result in decreasing instrument rotation rates, and even stalling, under load[126]. The air turbine remains the most popular type of high-speed handpiece in the USA and is likely to be found in most dental offices worldwide as the main means of cutting dental tissues[2, 96, 127].

### 5.2.2 Low-speed, high-torque handpieces

Despite the emergence in the 1950s of more efficient tools for removal of enamel at high speed, there remained a need for further development of slower speed instruments with higher torque[96]. High torque is important for adequate tactile feedback whilst removing softened dentine from the base of a cavity[6, 28]. Low-speed cutting was carried out using cord arm driven handpieces until the 1960s saw the arrival of KaVo’s Intra handpiece[90]. The wheels and cogs within the shaft allowed gear reduction of 2:1 or direct transmission (1:1)[90]. With the drive coming from the Dentatus air motor located within the handpiece, the operator benefited from a greater freedom of movement[3, 90].

Shortly after this, small electric motors were adapted for dental use by the Kerr Company[3, 90]. The ‘Electrotorque’ handpieces provided the high torque necessary, whilst operating more quietly than the noisy air motors[3, 90]. Air motors remain in common usage, but it is the electric motor that has recently been further developed for high-speed cutting (see section 5.3.3).

## 5.3 Types of modern handpieces

There are several manufacturers and many models of dental handpieces. They can be classified in a number of different ways, such as speed (slow or high) or power source (compressed air or electricity). W&H have produced a useful illustration to summarise the range of clinical applications and speeds at which handpieces operate (Figure 5.1).

### 5.3.1 Power sources

A high-speed dental turbine uses a current of air passing over its blades to provide energy which then turns the rotary cutting instrument, operating in much the same way as a windmill or waterwheel. Dental surgeries therefore incorporate units that compress air to be fed into the turbine handpiece.

Either air motors or electric motors may provide power to slow-speed handpieces. Like the air turbines, air motors are driven by compressed air, and so are connected to conventional dental units in the same way. Operating at 5 to 20 krpm, they are cheaper to buy and maintain than electric motors. As the air motor has more moving parts than an electric motor, it is more likely to produce vibration due to wear[28].

In his personal account, Christensen[128] showed a preference for electric motors at slow speed than air motors. Although the air motor is less expensive, it is more difficult to control operating speeds, and vibrations can be more pronounced[28]. As they require electricity to function rather than compressed air, dental units must be adapted to cater for this, although stand-alone conversion units are available. Air motors are common in the UK, whilst in the USA electrically powered motors are becoming increasingly popular[127].

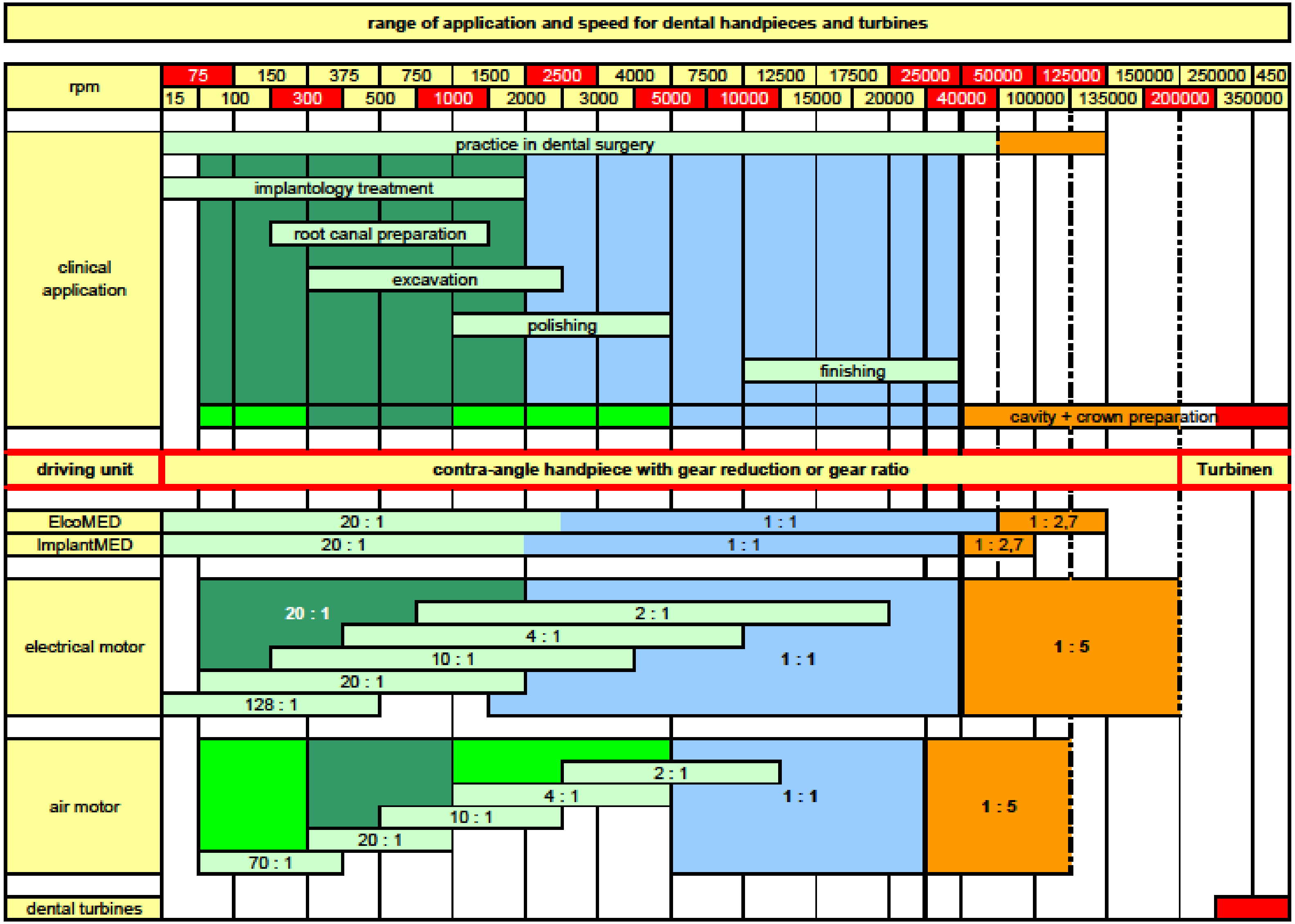

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Figure 5.1: Types of dental handpieces and turbines, showing ranges of RCI speeds in revolutions per minute (rpm). Courtesy of W&H.

Handpieces are operated by means of a foot pedal, which also controls instrument rotation speed[91] depending on pressure applied and positioning of the pedal.

### 5.3.2 Handpiece gears

Although motors are limited in their ranges of rotation velocity, different handpieces have been designed to incorporate gear systems in order to extend this range by either increasing or decreasing the speed of application. The gear ratio is usually indicated on the handpiece itself, often with a coloured band.

In practice, direct transmission is generally used for polishing and finishing of restorations. Motors have a greater longevity when operated at maximum speed, therefore when slower speeds are required, it is advisable to use handpieces to reduce the speed at the RCI. Slow speeds of rotation are required in a number of clinical situations, such as cutting bone for implantology treatment, preparation of a root canal, and excavation of carious dentine. These procedures would typically necessitate rotations under 2 krpm.

Most handpieces are of a one-piece design but some slow-speed handpieces are supplied with a detachable head, which may itself contain gears. This allows for a “mix and match” style combination of handpieces and heads, so that a range of operating speeds can be achieved.

### 5.3.3 High-speed, high-torque handpieces

It is now possible to operate high-torque handpieces driven by electric motors at rotation speeds of up to 200 krpm. These handpieces, often referred to as ‘speed-increasing’ due to gearing ratios of up to 1:5, are being directly compared against air turbines as an alternative means of cavity preparation[6, 127]. An advantage of this higher torque is an increase in tactile sensation for the operator[6], and also avoidance of stalling[126]. These handpieces ideally need to be used in conjunction with electric motors, as the higher speeds (above around 100 krpm) are not possible with air motors.

Watson *et al.*[6] concluded their evaluation of high and low torque handpieces with the observation that speed-increasing handpieces are no more likely than air turbines to produce enamel cracking or increases in temperature. Kenyon *et al.*[127] also found no evidence to suggest that the quality of cavity preparations differed significantly between the two types, although the speed-increasing handpiece has been demonstrated to cut more efficiently under load[126]. The principal disadvantages of the high-speed, high-torque handpiece are that it is larger, 50 to 100% heavier, and more expensive (at twice or three times the cost) when compared to an air turbine[96, 126, 127]. It has been claimed that speed-increasing handpieces produce less vibration[127], but this conclusion was based upon operator observations rather than quantitative assessments.

### 5.3.4 General handpiece designs and features

Handpieces used inside a patients' mouth are contra-angled in order to improve accessibility. These include specialised designs such as some surgical handpieces, or models with smaller heads (but lower torque) for working in a restricted space such as a child's mouth. Conventional straight handpieces are used in laboratory situations or for trimming acrylic dentures at the chairside, but not for direct patient contact. There are also some straight handpieces for surgical procedures at the front of the mouth.

For many applications, and certainly at high speeds, a spray of air and water is directed onto the RCI to counteract the adverse effects of heating. Most handpieces have an internal tube to supply this water, with one or more outlet ports on the head. External tubes can be found attached to some models, and others (for slow-speed use only) are available with no water coolant at all.

To improve visibility, many styles of handpiece are offered with an inbuilt fibre-optic light to illuminate the area around the RCI. When these are attached to a motor, the motor itself must be of an appropriate design so that the energy supply to the light is not interrupted.

### 5.3.5 Handpiece connections

The flexible tube that links the dental unit to the handpiece carries supplies of air, water and sometimes electricity (for light and/or an electric motor). The outlet patterns of these tubes must match with the pattern of the handpiece or motor. The main configurations are known as MidWest, Borden, and Sirona.

In basic systems, handpieces and motors are screwed directly onto the tubing. In order to facilitate detachment for regular cleaning and sterilisation, some manufacturers have developed additional multiple coupling connectors with rotatable joints, effectively offering a 'quick-release' system[75]. These connectors screw onto the tubing, but the motors and high-speed handpieces attach to them simply by pushing (and detach with a sharp tug). Examples are KaVo's Multiflex coupling and W&H's Rotoquick coupling.

The coupling between a motor and a slow-speed handpiece is also found in various configurations, but most modern designs use an 'E'-fitting, in accordance with international standards[129]. With all these different arrangements of components available, it is important to carefully consider and match up each part so that the whole system is fully functional.

## 5.4 Types of rotary cutting instruments

Rotary cutting instruments (RCIs) insert into the chuck of a dental handpiece in much the same way that a bit fits into a standard workman's drill. They are commonly referred to as burs, although strictly this title only refers to those with bladed cutting flutes. There are many shapes and sizes of RCIs for different purposes[28]. For example, a cylindrical instrument (such as a 'fissure bur') is primarily used to cut large cavities[91]. A large round (or 'rose-head') bur is used at low speed to remove carious dentine[91].

The most common materials used in the manufacture of RCIs are steel, tungsten carbide and diamond. Steel burs are the cheapest option, and are used at low speeds with a short working life[91]. Tungsten carbide can be used for the whole bur, or as the cutting tip only, mounted on a steel shaft[19]. Higher quality RCIs are constructed of steel with a coating of diamond. Figure 5.2 shows the ends of both a diamond instrument and a tungsten carbide bur, as viewed by means of scanning electron microscopy. The differences in construction are clear – the first picture shows tiny pieces of diamond embedded into an electro-deposited metal film, providing a rough surface which grinds shavings of dental tissues away through abrasion. The tungsten carbide bur however is manufactured from one material which is shaped into cutting flutes that slice into the tissues. These tend to become blunt more rapidly than diamond instruments, and are discarded after fewer uses[91].

a)

b)

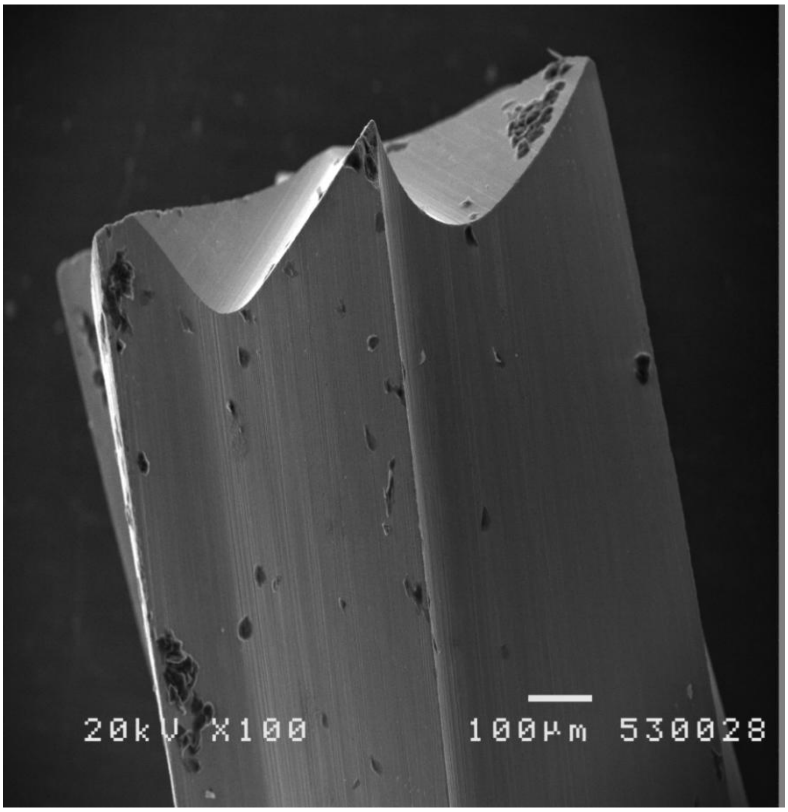


Figure 5.2: Scanning electron microscope images (x100) of the ends of two types of cylindrical cutting instruments a) diamond and b) tungsten carbide.

Shaft diameters generally differ depending on whether they will be used in a slow-speed handpiece (2.35 mm) or high-speed turbine (1.60 mm)[91]. Chuck mechanisms for securing a RCI in place also vary. Modern handpieces are increasingly being equipped with friction-grip chucks, where the RCI is released by pushing a button on the back of the handpiece head. These result in less vibration than the conventional latch-grip (lever chuck) systems, which grip the instrument less firmly[28].

## 5.5 Handpiece testing

In their review articles of 1993, Dyson and Darvell[3, 95] noted that the development of dental handpieces had been largely empirical. Their subsequent work over a number of years has endeavoured to expand understanding of air turbine performance in particular[125, 130-134]. Initial measurements of gas flow, free running speed, torque, power and efficiency provided some reference data against which further evaluations could be assessed[131, 132].

Brockhurst & Shams[135] attempted to provide a less sophisticated means by which dentists could check the power performance of their handpieces, recommending a stall torque test for use in the clinic. However it was conceded that the test would not identify handpieces that were under-performing due to excessive vibration.

Having recognised the need for a standardised means with which to test and compare handpiece characteristics, Darvell and Dyson[130] published the recommendations for a machine designed specifically for this purpose. This machine was subsequently used by Monaghan *et al.*[125] to test air-turbine handpieces in everyday use and compare longevity over a period of 30 months. Free-running speed was found to decrease as bearings became resistant, and an increase in sound output seemed to act as a predictor of bearing failure. The monitoring equipment was an apparent success, but it was acknowledged that additional comprehensive tests with larger sample sizes would be required in order to investigate more of the conditions that handpieces are exposed to in practice.

## 5.6 Physical characteristics

There are a number of factors affecting the reactions of the dentine-pulp complex to the destruction of dental tissues by rotary instruments, including heat and pressure[75].

### 5.6.1 Heat generation

The friction generated during dental cutting can lead to production of high temperatures, and has the potential to cause damage to the dental pulp. The design of high-speed handpieces therefore evolved to incorporate a cooling system in the form of a water spray mechanism as an essential component[4, 96]. The compensatory cooling effect of the water spray has been confirmed to be efficient by laboratory studies[4, 6], even to such an extent that following cavity preparation a reduction in temperature was reported[6].

In the research environment, temperature changes during cavity preparation can be measured by placing thermocouples into the pulp chamber or close to the area being cut[4, 6, 136]. A thermal imaging device has been used to record in-vivo tooth temperatures[137] and to observe heat generation during ultrasonic scaling[138]. It may be possible to use this equipment for additional investigations of the heat produced by the action of cutting instruments.

It has been demonstrated that significant damage is no more likely with high-speed handpieces than with conventional low-speeds[96]. Similarly, high-torque (speed-increasing) handpieces do not cause an increase in temperature when compared with conventional air turbines, although operating speed may have some influence. Diamond RCIs were found to produce marginally higher temperatures than tungsten carbide burs, perhaps due to the effects of friction or the cooling action of the blade flutes[6]. Cavalcanti *et al.*[4] demonstrated that increases in load are directly related to the generation of heat; an influence that was also acknowledged by Öztürk *et al.*[5]. Temperatures during cutting are also affected by the wear of a tool and its effectiveness[82].

### 5.6.2 Forces applied during cutting

Many of the studies of dental cutting recognise the influence of force applied to the RCI, and some attempts have been made to record the usual loads naturally applied by dentists whilst preparing teeth using rotary instruments.

Ohmoto *et al.*[139] measured the applied load whilst bovine dentine was cut with carbide burs in turbine handpieces. This comparison of two techniques suggested that the maximum loads applied during a continuous cutting procedure (20 to 60 g) were greater than those generated during intermittent cutting (30 to 40 g), and that a greater load was applied vertically than horizontally. Liao *et al.*[140] extended this work to investigate three techniques using diamond RCIs in both enamel and dentine. Loading in this study ranged from approximately 35 g when cutting in a horizontal motion in dentine, to a maximum of 105 g when cutting enamel vertically.

The main limitation of both of these studies is that only one dentist carried out the cutting for each. The argument for this was that reproducible data were required, and that cutting procedures varied depending upon the operator[139]. Whilst there is evidence of operator-dependent variation in cutting technique[141], it is for this same reason that a greater number of operators would need to be investigated to obtain a general reference for clinical loading. This was recognised by Liao *et al.*[140], and suggested it as a potential future direction for research.

A crude test of applied force was performed by Siegel and Von Fraunhofer[12]. A RCI was inserted into the chuck of a handpiece, which was held freely by a dental practitioner. They were instructed to press the end of the RCI onto a balance with the force that they would usually use in practice. This exercise was repeated for six operators, and the mean load was determined to be 99.3 (± 23.4) g.

Elias *et al.*[142] measured the magnitude of forces applied to the teeth during lateral cutting with two types of turbine. The extracted teeth were mounted on a custom-made force measuring unit. In comparing variables such as wet or dry cutting and RCI type, no significant differences were found. However, operators (n=31) were found to apply a average force of 1.44 N when using the turbine which had the higher torque, whereas with the lower torque handpiece the mean cutting force was significantly lower at 1.20 N.

Abouzgia and James[143] measured shaft speeds whilst drilling through bone under load forces between 1.5 and 9.0 N. A key finding of this study was that high forces can reduce the operating speed by as much as 50%. A comparable result was obtained by Sorenson[144], using an air-turbine handpiece, where bur rotation speeds were markedly reduced (by almost 100 krpm) when lateral loading was only slightly increased (from 50 to 60 g).

### 5.6.3 Vibration measurement in dentistry

Henry and Peyton[11] published some of the earliest calculations of vibrations relating to dental cutting. They recorded characteristic frequency waves using a record player needle to detect vibrations in a block of ivory under the influence of cutting instruments. Though limited by available technology, their attempts gave some momentum to the notion of high-speed dentistry. Other traditional means of measuring vibrations include accelerometers, strain gauges and microphones[133, 145]. Light microscopy has been used to measure vibration displacement of sonic scaling tips, which are powered by compressed air and oscillate within the same frequency range as high-speed handpieces[146]. Significant discrepancies were found when displacement amplitudes were measured in instruments from different manufacturers under identical conditions.

Rytkönen & Sorainen[147] used a piezoelectric charge accelerometer to measure handpiece vibration: movement of the handpiece would have been detected by the compression of a piezoelectric crystal element, which releases a charge in proportion to the vibration amplitude and frequency. They attempted to test the influence of various conditions on vibrations of new and used dental turbines and micromotor (speed-increasing) handpieces. Unfortunately crucial details were omitted from the description of methodology and results, and no statistical analysis appears to have been attempted, casting doubt upon the reliability and validity of the conclusions.

### 5.6.4 Laser vibrometry in dentistry

The use of accelerometers for the measurement of handpiece vibration is not ideal, as the mass of the accelerometer attached to the handpiece may affect the accuracy of the results[112, 148]. A modern alternative is to utilise the technique of laser vibrometry, which offers the advantages of high accuracy and sensitivity, whilst its non-contact nature avoids damping[149-151].

Laser vibrometry has been used successfully to scrutinise the oscillations of ultrasonic scaler tips both when vibrating in air and in contact with teeth. The effects of water flow rate, power setting and loading of the instruments have been demonstrated, and a number of factors of clinical importance have been highlighted[150-153]. Oscillations of other dental instruments (such as endosonic files) have also been characterised using this method[154-156]. Castellini *et al.*[149] advocated laser vibrometry as a practical tool for the assessment of tooth mobility under dynamic loads. The data achieved using this method correlated well with results obtained in earlier evaluations of displacement, in which a static load had been applied[43].

Takamori *et al.*[112] compared the vibrations of teeth, using a laser Doppler vibrometer, whilst cavities were prepared using a high-speed dental turbine and an Er:YAG laser. They concluded that greater vibrations had been caused by drilling with the high-speed handpiece. Also of note was the observation that the frequency spectrum of the turbine, at around 5kHz, was close to the range of high sensitivity of the human ear (1 to 5 kHz), whilst the Er:YAG laser displayed a frequency characteristic approaching 230 Hz.

Building upon their earlier work on handpiece vibration, Rytkönen & Sorainen[157] introduced a laser vibrometer for simultaneous comparison with accelerometer recordings, with both methods producing similar results. Again there were weaknesses in their report, which offered no indication whether the correlation between techniques was statistically significant.

Poole *et al.*[158] measured vibrations of turbines and speed-increasing handpieces using a scanning laser vibrometer.  Areas scanned at the head end of the handpieces vibrated more than those further from the rotary instrument.  Significant differences were also found between different handpiece models.

### 5.6.5 Wear of tools/longevity of handpieces

The frictional forces of cutting result in wear of tools, which will affect the rate of tissue removal and surface finish.  There is a close association between temperature and wear.  Plastic deformation during cutting produces an audible sound; as tools become worn, the pitch changes[82].

Scanning electron microscopy has been used to examine changes in the appearance of small dental cutting instruments through repeated use[136, 159, 160].  Watson and Cook[19] observed cutting interactions using video-rate confocal microscopy.  They revealed that inadequately engineered RCIs tended to revolve eccentrically, and were therefore expected to produce vibrations.  Erratic movement of RCIs led to uneven wear and deformation of blade surfaces, generating a micro judder and roughness of the cut surface.  Eccentric rotation of RCIs could alternatively be attributed to the handpieces themselves.  Leonard and Charlton[13] measured RCI displacement in nine models of turbine handpieces using a standard test mandrel.  None exceeded the ISO standard[161] of a maximum 0.03 mm of eccentricity.  Five models were tested again after 1000 cycles of use.  Although they all exhibited significantly increased eccentricity, they still met the required standard.

Much of the available literature on dental cutting and drill efficiency relates to drilling into alveolar bone in preparation for dental implants.  Wear of these tools reduces efficiency and the resulting friction produces additional heat[136, 160], with a possible influence on vibration. Cleaning and sterilisation procedures have been shown to affect the rate and nature of deterioration of dental instruments[162]. Tanaka *et al.*[159] used scanning electron microscopy to look at the wear of tungsten carbide burs when used to cut bovine dentine three times at four loads. This subjective evaluation concluded that the burs were 'little affected' by wear after an apparent 12 uses, of 5 seconds duration each. Galindo *et al.*[163] also examined SEM images before and after a diamond RCI was used to make 60 cuts of 2 mm each into human molar teeth, and observed blunting of the RCI surface. The limitation of the assessment technique was recognised, and suggestions were given regarding possible methods for quantifying the extent of the wear.

In a test of the effects of wear of RCIs whilst cutting a machinable glass ceramic, a significant reduction in efficiency ($p < 0.05$) occurred between 2½ and 5 minutes of cutting for two types of conventional diamond RCI[12]. A third type of diamond RCI showed no difference in the mean amount of substrate removed as time progressed. Under the same conditions, a tungsten carbide bur removed more substrate in the initial 2½ minutes than the diamond instruments, but in the subsequent 2½ minutes a highly significant reduction in efficiency was observed ($p < 0.001$). It was recognised that the properties of the artificial cutting substrate may have influenced this effect. Nevertheless, the less rapid deterioration of diamond RCIs lead to the recommendation that they should be preferred for procedures requiring extended enamel preparation.

Testing of turbine handpiece performance subjected to simulated clinical use has indicated that properly maintained handpieces should be expected to function for at least 500 cycles (or approximately one year), without loss of performance[13].

## 5.7 Biological effects

Using dental handpieces involves removal of some sound tissue (particularly at high speed), even when the treatment is only to replace an existing restoration[67]. As handpieces are hand-held, the unrestricted movements of both patient and operator result in erratic interactions between tooth and cutting instrument[19], with precision limited to 1 or 2 mm at best[107]. It has been demonstrated that pulpal repair mechanisms are triggered by dental cutting procedures in the absence of caries[60]. Damage is often also caused to an adjacent tooth if the teeth are in close proximity to one another[67].

### 5.7.1 Enamel cracking

Some degree of cracking exists naturally in dental enamel in the form of structures such as lamellae[6, 15]. It has been known for some time that dental cutting instruments are capable of inducing and increasing sub-surface cracking in enamel during normal operative interventions[7, 164]. Where cracks weaken enamel, there is a danger that shrinkage of an adhesive restorative material will increase cracking[6, 19, 165]. Hence the effectiveness of the seal around the restoration is reduced[6, 19], and the cracks will be receptive to new carious attacks[116]. Analyses of iatrogenic cracking therefore are of clinical relevance, but the mechanism by which the cracks propagate is a complicated process[14].

Kasloff *et al.*[7] used the penetration of a fluorescent dye to indicate cracking. A higher incidence of severe cracking was seen in teeth prepared using carbide burs than in those cut using diamond RCIs, although Watson *et al.*[166] later found no significant difference between the instrument types in their confocal microscopy examinations. Video-rate confocal microscopy has been used to directly observe the fragmentation of enamel whilst cutting with different types of RCI, which was particularly evident where enamel prisms are unsupported[19]. It was demonstrated that differences in the engineering of RCIs affected the extent of subsurface enamel cracking, which extended 5-15 prism depths into the tooth.

Another investigation carried out by Watson and his colleagues[6] examined cracks initiated as a result of cutting with high and low torque handpieces. This confirmed that sub-surface cracking significantly increases when enamel is cut, but noted that the handpiece type (high-speed low-torque or high-torque speed-increasing) did not appear to affect this result. This was similar to the conclusion drawn by Kasloff[7], describing no direct correlation between speed of rotation and crack occurrence. Kasloff's report also noted that a high-speed instrument powered by water turbine had produced fewer cracks than an air turbine and a low-speed belt-driven handpiece.

### 5.7.2 Smear layer

Instrumentation in the preparation of cavities results in the deposition of a layer of debris on the cut surfaces of enamel and dentine, known as the smear layer[8, 15]. Research has concentrated on the smear layer of dentine, as this is known to affect the permeability of the tissue and consequently bonding of restorative materials[99, 167]. The enamel smear layer may also affect bonding but less has been determined about its ultrastructure[168], and adhesion to dentine is more of a challenge due to its higher organic content and tubular structures[15].

When observed under scanning electron microscope, the dentine smear layer appears as a 1-2 μm coating of debris[99]. This apparently amorphous structure is made up of particles of dental tissues, and an organic film[8]. The debris also infiltrates the dentine tubules forming 'plugs'[167]. Although the tubules are then occluded, bacteria may be contained in the material and adherence to the surface is difficult[15].

The nature of the smear layer differs depending on the cutting instrument or preparation method used. Hand instruments deposit a thick layer of debris on enamel surfaces[79]. After acid etching, a dentine surface cut using a carbide steel bur has been found to be significantly more permeable than that prepared using a diamond RCI[169]. There were also differences in surface characteristics produced with diamond RCIs and finishing RCIs[167]. There is evidence that removing caries chemically (eg using Carisolv) or by laser ablation does not result in a full smear layer and leaves some tubules exposed, which may improve the adhesion of restorative materials[76, 170]. A smear layer has also been found as a result of using rotary instruments during endodontic preparation of root canals[86].

### 5.7.3 Patient discomfort

Sources of discomfort for the patient undergoing restorative treatment are principally attributed to the heat generation and vibrations of the instruments used in cavity preparation[11]. The effects of dental handpiece vibration have been studied since at least 1949, when patients were invited to report their perceptions of vibrations at various frequencies[95]. High-speed rotary instrumentation is better tolerated than conventional slow speeds in this respect, as the vibrations are less discernable at speeds over 40 krpm[28]. Operators have been advised to deaden the extent of these movements using digital pressure and by ensuring that handpiece bearings are not failing[171].

The relationship between vibration and pain is complex. There is some evidence that similar areas of the brain are involved in processing the sensory information for both stimulants; an association between them can be made where memory processes are integrated with these pathways[172]. An interesting finding is that high frequency vibrations are not always perceived as unpleasant, and can in fact be used to *reduce* pain. This is known as vibratory analgesia, and has found a dental application in the relief of temporomandibular joint disorders[173]. It is assumed that this concept was also the inspiration for a dental handpiece that has been designed to vibrate in order to give an anaesthetic effect (Japan patent 2003250814)[174].

## 5.8 Effects on operator

Operators of dental handpieces include dental surgeons, hygienists, therapists and technicians. They can suffer from adverse effects of regular handpiece use, particularly as a result of long-term exposure.

### 5.8.1 Aerosol production

One consequence of using an air-water spray for cooling an instrument whilst cutting is that bacteria may be released as an aerosol. This may infect adjacent teeth and can also be released into the air surrounding the treatment area, exposing the operator to potentially hazardous air-borne particles. This highlights the value of isolating a tooth with rubber dam and using efficient aspirating equipment whilst cutting[71].

### 5.8.2 Auditory damage

Several researchers have taken an interest in the harmful effects of noises produced during dental cutting operations, which may contribute to hearing loss for staff after prolonged exposure[9, 175-177]. Bahannan *et al.*[175] noted differences in noise intensity and frequencies according to handpiece type, and considered some design features that may be responsible for this variation.

### 5.8.3 Hand-arm vibration syndrome

There are accounts in the literature of dental staff experiencing vascular and neurological symptoms in the upper limbs, which are attributed to the high frequency vibrations of dental tools[10, 147, 178, 179]. This condition is termed "Hand-Arm Vibration Syndrome" (HAVS). In 2005 a Physical Agents (Vibration) Directive (2002) was implemented across the European Union in an attempt to reduce occupational exposure to risks associated with vibration. The method for measuring hand-tool vibration was documented by the International Organization for Standardization (ISO)[148, 180]. Although Mansfield[10] concluded that the magnitude of vibrations in the dental profession are well within the limits enforced by the Directive, he encouraged handpiece manufacturers to increase the efficiency of their products in order to minimise exposure times.

In an interesting study by Concettoni and Griffin[181], a scanning laser vibrometer (SLV) was used to detect the transmission of vibrations across the fingers, hand and arm. The 14 participants each pressed against a vibrating metal plate at frequencies up to 500 Hz. The fingertips were found to resonate at higher frequencies than the thicker areas of the hand and arm. It may be possible to apply this technique to investigate the transmissibility of the high-frequency vibrations generated by dental tools.

# CHAPTER 6

# MATERIALS AND METHODS

## 6.1 Introduction

The aim of this study was to evaluate the vibrations of dental handpieces in a non-contacting manner. Vibration analyses were carried out using a Scanning Laser Vibrometer (SLV), the operating principles of which are described in more detail below (6.2). The experimental conditions investigated were:

1) **Unloaded**: Measurement of vibration displacement amplitudes of dental turbines and speed-increasing handpieces whilst operated in air, with and without a RCI (rotary cutting instrument).
2) **Loaded**: Measurements were repeated on some of the turbines whilst they cut into teeth at known loads.
3) **Tooth/RCI exchange**: The final study was performed to determine whether changing the RCI or the cutting substrate (ie tooth) would contribute to variations in vibration.

## 6.2 Laser vibrometer operating principles

A laser vibrometer is a device capable of measuring the frequency, velocity, acceleration and displacement of a vibrating object. The system exploits the Doppler Effect – a phenomenon that describes how waves (sound, light etc) reflected off a moving object are altered in frequency depending on speed and direction of movement of the object in relation to the original source of energy.

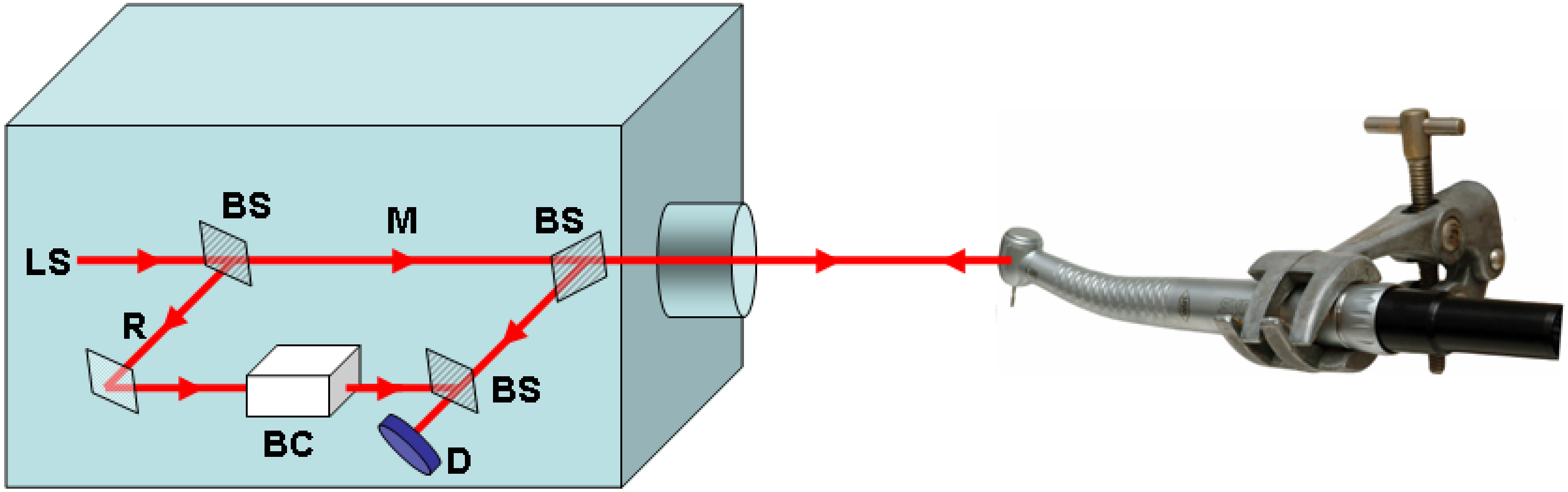


Figure 6.1: Schematic diagram illustrating the path of a laser from its source (LS) to the detector (D) within the scanning head of a laser vibrometer. Beamsplitters (BS) are used to divide the laser into measurement (M) and reference (R) beams, and a Bragg Cell (BC) aids the interpretation of the interference pattern of the reflected light. A dental handpiece represents the vibrating object. From Poole *et al.*[158].

The laser vibrometer detects differences in the frequency of reflected light when compared against a reference beam; the shift recorded relating to the velocity of the object. The displacement amplitude is calculated by the pattern generated by the reflected beam as it interferes with the reference beam. This has been illustrated using a schematic diagram (Figure 6.1), to show the path of the laser.

A laser beam of wavelength 632.8 nm is emitted from a helium-neon source (LS). At the first beamsplitter (BS), this divides into a measurement beam (M) and a reference beam (R). The measurement beam is focused upon the target object (represented in this case by a dental turbine handpiece), and undergoes a shift in frequency at the point of reflection according to the Doppler Effect. This signal is received by the scanning head, and is proportional to the velocity of the moving target. The reference beam remains within the scanning head and is diverted through a Bragg Cell (BC), which enables determination of the direction of movement (towards or away from the laser source), before recombining with the frequency-shifted measurement beam. The resulting interference pattern at the detector (D) allows calculation of vibration displacement amplitudes to a resolution of 2 nm. If measured at several points on the surface of an object, its movements can then be characterised as an animation superimposed over a video image.

### 6.2.1 Reference signal

An important component in the equipment accompanying the laser vibrometer is a transducer that acts as a reference signal. Vibrations occur in cycles, and each repeated measurement must be taken at the same phase of the cycle. Reference signals can be monitored using various types of transducers depending on the type of object under investigation. For example, microphones can act as a detector of a reference signal in objects that emit an audible sound at a frequency that relates to their vibrations.

## 6.3 Vibrometry methodology

Handpiece vibrations were measured using a PSV-300-F/S High Frequency Scanning Vibrometer System (Polytec GmbH, Waldbronn, Germany). The main components of the system were a scanning head which housed the laser and had an integrated video camera (OFV 056, Polytec GmbH, Waldbronn, Germany), and a workstation comprised of a processing unit connected to a keyboard, mouse and monitor. A reference signal was used to synchronise the phase of the vibration cycle, which in handpieces correspond with the rotation of the RCI. As the turbines produced an audible sound, it was possible to use a microphone (Sekaku Dynamic Microphone KUD-626, Sekaku Electron Industry, Taiwan), with a pre-amplifier to boost the low-voltage signal, and use this as the reference signal. The quieter speed-increasing handpieces were powered by electric motors, so the reference signal in these instances was obtained by placing a wire coil transducer[151] adjacent to the motor, so that it detected the electromagnetic field and consequently the frequency. Figure 6.2 shows the vibrometer scanning head, with the laser beam directed onto a speed-increasing handpiece.

The specific points on the handpiece from which to obtain measurements were marked on the monitor by superimposing individual points onto a captured video image of the handpiece. The laser beam was aligned with the points on the image, and focused to facilitate the reception of the reflected signal. This prepared the SLV software, so that during each scan the laser could rapidly locate the desired scan point location and detect the vibrations occurring at that position.

Vibration data were collected over a frequency range of 0.5 to 20 kHz. Data at frequencies under 0.5 kHz were excluded due to high noise levels. Ten measurements were taken under each condition. The SLV software produced graphical representations of frequency spectra, where a peak in velocity indicated the fundamental vibration frequencies of handpieces. The frequency resolution was ±12.5 Hz. Vibration data obtained at these particular frequencies were selected for further interrogation and exported as an ASCII file. This text file contained details of maximum vibration displacement amplitudes at each scan point position, and the frequency they were recorded at.

### 6.3.1 Statistical analysis

Exported data were initially explored using Microsoft Excel then manipulated further using the Statistical Package for the Social Sciences (SPSS) for Windows (Release 15.0.0, 2006. Chicago, USA: SPSS Inc.). As there was one dependent variable and several independent variables, a univariate Analysis of Variance (ANOVA) with a significance level of $p = 0.05$ was carried out for each condition, followed by post hoc testing where appropriate. Levene's test was used to find out whether the assumptions of a parametric test were being met by finding out whether error variances were equal. Where population variances were unequal, Welch's *F*-ratio was used to measure the ratio of variation due to individual differences against the variation caused by experimental manipulation. Games-Howell tests are also appropriate for use when homogeneity of variance is violated, and particularly applicable to small samples. Therefore Games-Howell tests were used to determine which groups had means that differed significantly from one another.

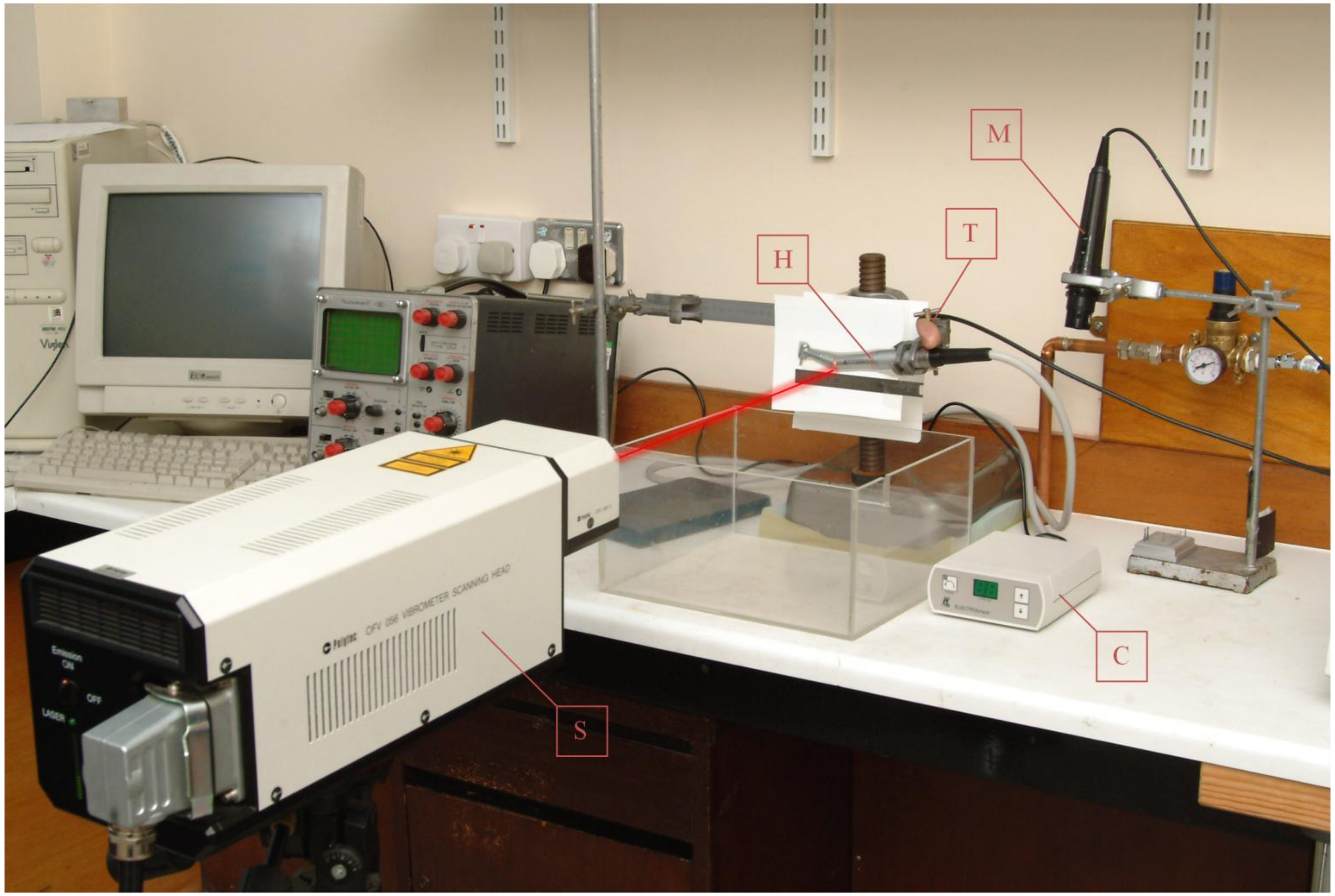


Figure 6.2: Arrangement of equipment for unloaded measurements. The path of the laser beam is indicated by a red line. The beam is directed from the scanning head of the vibrometer (S), toward the vibrating handpiece (H). In this example, a speed-increasing handpiece is being regulated by a table-top control unit (C), and the metal coil transducer (T) is acting as the reference signal. The nearby microphone (M) is for use with turbine handpieces, and would be arranged close to the top of the handpiece head.

### 6.3.2 Calculation of rotation velocities

Peaks in the frequency spectra indicate where the maximum vibration velocities occurred (Figure 6.3), and can be used to calculate the rotation speed of the RCI. The fundamental vibration frequencies of unloaded handpieces were used to calculate instrument rotation velocities by applying two equations. Equation 6.1 converts the detected frequency, measured in kHz, to Hertz by multiplying by 1000. This is then converted from seconds to minutes by multiplying by a factor of 60 in order to give a rotation speed in units of revolutions per minute (rpm).

$$\text{frequency (kHz)} \times 1000 \times 60 = \text{rotational speed (rpm)} \qquad [6.1]$$

In order to conform to the International System of Units (SI) for angular velocity, equation 6.2 was then also applied:

$$1 \text{ rpm} = 2\pi \text{ rad/min} = \frac{2\pi}{60} \text{ rad/s} = 0.1047 \text{ rad/s} \qquad [6.2]$$

It was then possible to compare these derived speeds with the maximum rotation speeds documented in the manufacturers' literature. The percentage difference was calculated using equation 6.3:

$$\left[ \frac{\text{Documented speed of instrument rotation}}{\text{Derived speed of instrument rotation}} \times 100 \right] - 100 = \%\text{ difference} \qquad [6.3]$$

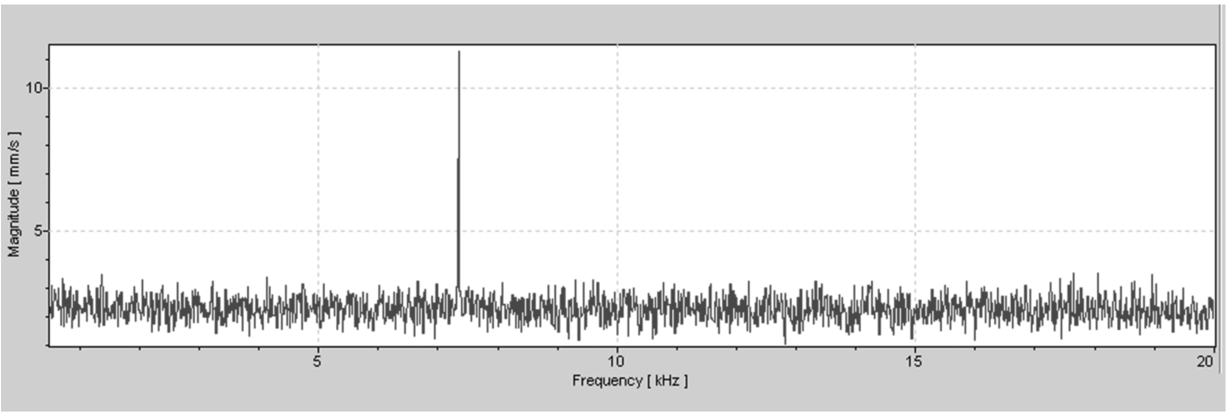


Figure 6.3: Example of average vibration velocity frequency spectrum recorded during a scan of KaVo's 637C (turbine handpiece with small head). A main vibration peak may be observed at 7.35 ± 0.01 kHz, corresponding to the speed of instrument rotation.

## 6.4 Experimental arrangement

All handpieces used during this research were new turbines or new speed-increasing handpieces provided by two manufacturers, KaVo (KaVo Dental GmbH, Biberach, Germany) and W&H (W&H Dentalwerk Bürmoos GmbH, Austria) – details are recorded in Table 6.1. The turbines were clamped firmly at the end furthest from the RCI; speed-increasing handpieces were supported likewise by clamping the electric motor. The preparation and arrangement of equipment for both unloaded and loaded conditions was initially alike.

Compressed air was supplied to the handpieces from an oil-free compressor (OF302-25B, Jun-Air, Denmark), via a portable dental unit known as an Esticart (KaVo Dental GmbH, Biberach, Germany). The speed-increasing handpieces required an additional table-top control unit in order to program the desired speed (Electrotorque - KaVo Dental GmbH, Biberach, Germany; Plug & Go - W&H Dentalwerk Bürmoos GmbH, Austria), which was connected to an electric motor provided by the corresponding manufacturer.

To prevent overheating of RCIs, handpieces were supplied with an air/water coolant spray. The water for this was held in a container attached to the Esticart unit, with a water flow rate through the handpiece of 40 to 50 ml/min. Before each set of scans was carried out, the drive air supply was measured using a pressure gauge adjacent to the handpiece connection, to ensure that it met with the manufacturers' recommendations. Handpieces were also regularly lubricated as instructed by the manufacturer.

Table 6.1: Details of handpiece models, including maximum rotary cutting instrument rotation speeds as documented in manufacturers' literature.

| Model | Manufacturer | Description | Speed (krpm) | Speed (rad/s) |
|---|---|---|---|---|
| WA-99 A | W&H[a] | Synea LS speed-increasing | 200 | 20944 |
| 25 CHC | KaVo[b] | INTRAcompact speed-increasing | 200 | 20944 |
| TA-98 CM | W&H[a] | Synea HS turbine | Up to 350 | 36652 |
| 660C | KaVo[b] | SUPERtorque turbine | 350 | 36652 |
| TA-96 CM | W&H[a] | Synea HS turbine (mini) | 370 | 38746 |
| 637C | KaVo[b] | BELLAtorque mini turbine | 400 to 480 | 50265 |
| TA-98 M | W&H[a] | Synea HS turbine (steel bearings) | Up to 350 | 36652 |

[a] W&H (W&H Dentalwerk Bürmoos GmbH, Austria)
[b] KaVo (KaVo Dental GmbH, Biberach, Germany)

## 6.5 Unloaded measurements

Six scan points along the side of each handpiece were selected from which to collect data (Figure 6.4). There were a number of factors that influenced the choice of scan points. Firstly, as the intention was to gain a general impression of vibrations at different areas of the handpiece, the points chosen were widely distributed across the surface. Secondly, it was important that each point was located where the surface of the handpiece was approximately perpendicular to the path of the laser beam, as this facilitated detection of the measurement beam as it was reflected back towards the scanning head. Due to the constraints of the vibrometer system, points could not be situated at the edges of the object under scrutiny. The RCI was not considered a suitable target as the SLV was not capable of differentiating rotational vibrations, and would not have been accessible in the either the 'no RCI' state or the anticipated loaded cutting study.

Figure 6.2 shows the arrangement of the equipment for the unloaded investigations. Maximum vibration displacement amplitudes of five turbines and two speed-increasing handpieces were measured whilst they were running unloaded in air. Recordings were taken whilst handpieces were equipped with and without cutting instruments. Where a handpiece was operated with a RCI, the same diamond instrument was used (Hi-Di 541, Ash Instruments Inc., Delaware, USA). Identical tests were also carried out but with the exception that no RCI had been inserted into the handpiece.

## 6.6 Loaded measurements

The arrangement of the equipment for the loaded experiments is illustrated in Figure 6.5. Three turbines were used to investigate maximum vibration displacement amplitudes of

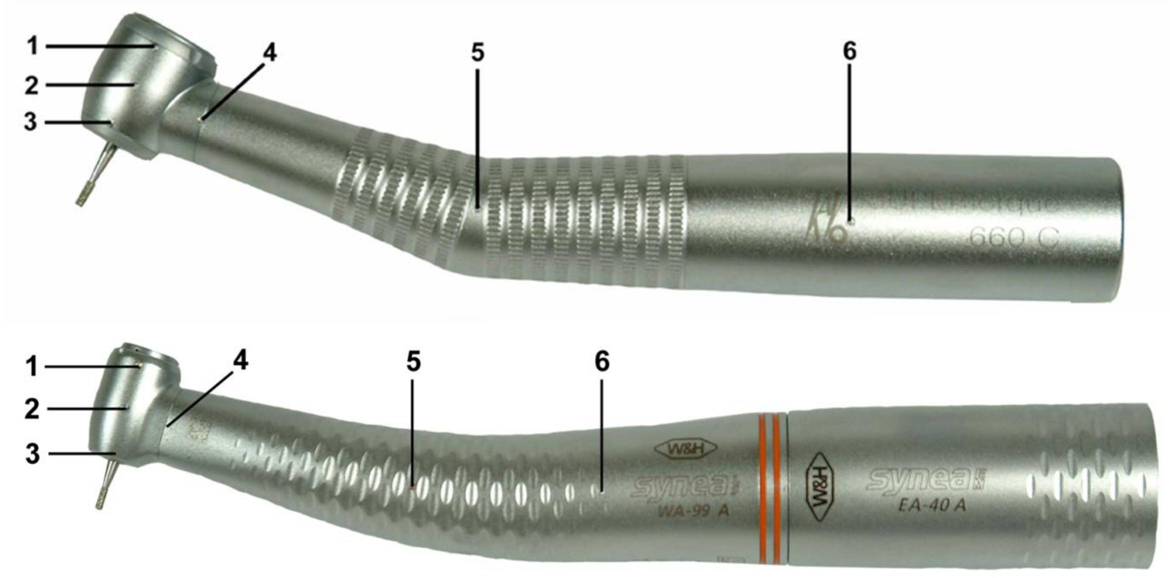


Figure 6.4: Scan point positions shown on a turbine (top) and speed-increasing handpiece.

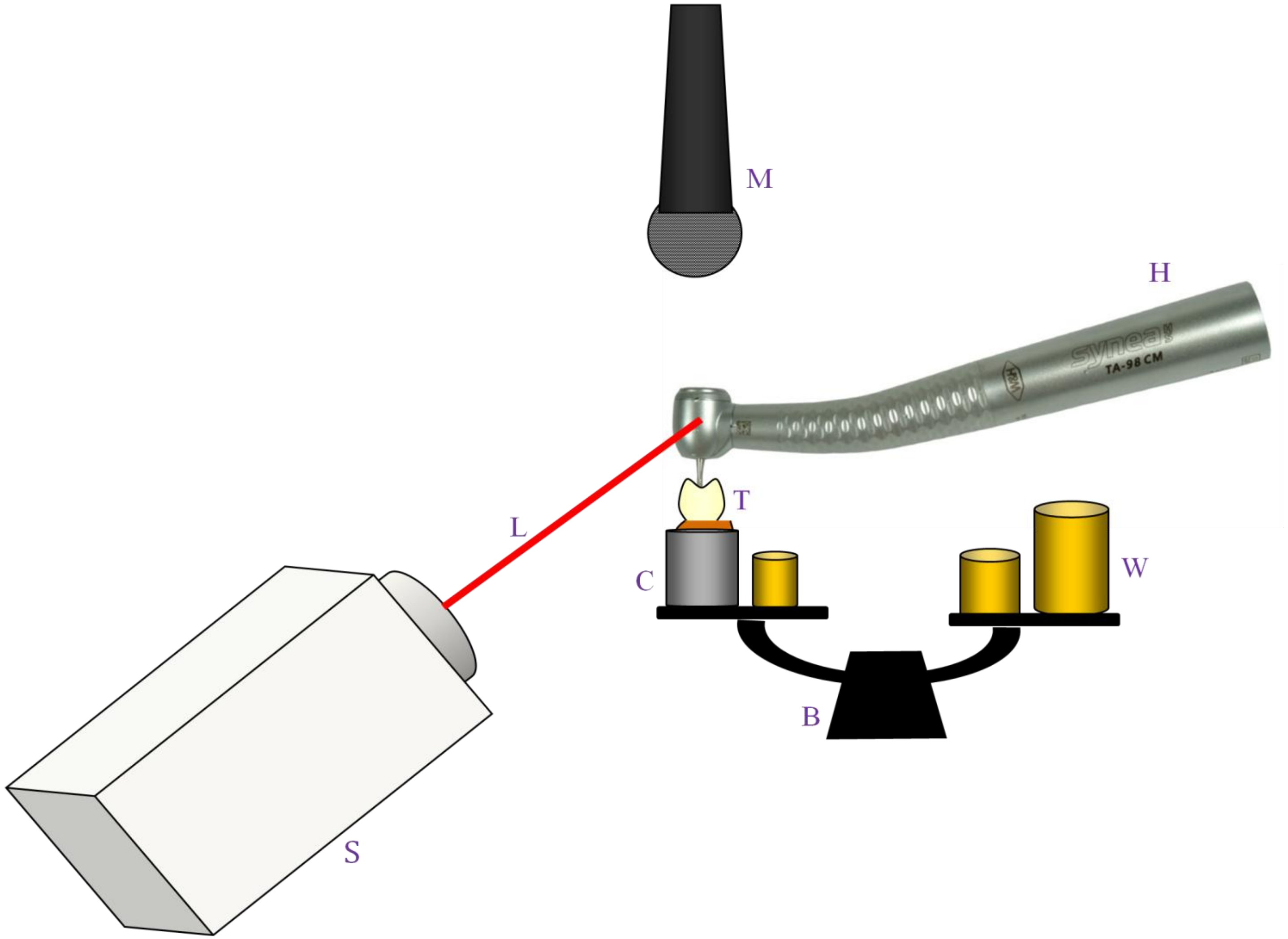


Figure 6.5: Schematic diagram of the arrangement of equipment for loaded measurements. The laser beam (L) was directed from the Scanning Laser Vibrometer (S), toward the turbine handpiece (H), which was supported by a clamp as it cut into a tooth (T). The tooth was encased in a cylinder (C) containing impression material, and set upon a pan balance (B) along with a number of weights (W). A microphone (M) was used to produce a reference signal.

handpieces whilst cutting teeth under load. Ten extracted, sound molar teeth were collected, stored and used in full compliance with Human Tissue Authority protocol[182]. Following extraction they were fixed in 10% formalin then washed and stored at -20 °C. The teeth were prepared by setting them individually into small cylinders containing vinylpolysiloxane impression material (Virtual Light Body, Ivoclar Vivadent, Ontario, Canada). The tooth roots were immersed within the impression material up to the level of the EDJ, leaving the crown exposed. Once the material was set, the whole cylinder was mounted onto a laboratory pan-balance.

The turbines used in this investigation were the TA98CM (W&H), 660C (KaVo) and TA96CM (W&H), details of which can be found in Table 6.1. It was necessary for the handpiece to remain stationary so that the laser could remain focused at a fixed location. This was important as conditions needed to be standardised in order to allow experimental comparisons to be made, and to allow the detection of vibration only (rather than any other handpiece movement). So rather than applying a moveable handpiece to a fixed substrate, the handpiece was secured in a clamp whilst a pan-balance was used to apply the load onto the instrument. Weights were adjusted either side of the balance so that the crown of the tooth contacted the rotating cutting instrument at a known load of 50, 100, 150 or 200 g. The foot pedal (which operated the handpieces) was depressed before cutting began, so that the instrument was already rotating prior to contact with a tooth.

Two types of cutting instrument were investigated – a diamond RCI (Hi-Di 541, Ash Instruments Inc., Delaware, USA) and a tungsten carbide bur (FG 57, Jet, Kerr Dental, California, USA) (Figure 6.6). Twelve new RCIs of each type were used, and were exchanged at the same time as the teeth were replaced and loads were changed. Cuts were made into the sound enamel. If the investigator observed that the instrument had entered into the softer dentine layer of the tooth, the scan was abandoned and another attempt was made at a different location on the surface of the tooth crown. Therefore a single instrument was sometimes used more than ten times in order to achieve ten successful scan measurements. To minimise the chances of wear (of the RCI) affecting the results, it was ensured that each instrument was used no more than 20 times. As a scan could be carried out within five seconds, this means that no RCI was cutting for more than 100 seconds in total. Data were collected from a scan point in the centre of the side of the head of each handpiece (corresponding to scan point 2, Figure 6.4). Analysis was carried out on ten measurements for each handpiece at each load and with each type of instrument.

## 6.7 Tooth/RCI exchange

As the exchange of RCIs and teeth occurred simultaneously in the loaded investigation, it was not possible to determine which of these variables was responsible for the results obtained. A third experiment was therefore devised in order to establish whether differences between teeth, or between instruments, were most likely to be responsible for differences in vibrations.

The procedure was the same as for the loaded study, with one main exception: instead of changing the RCI at the same time as replacing the tooth, all of the teeth were cut using all of the instruments. For example in the first scan, RCI 1 was used to cut tooth A, then in the second scan tooth B, third scan tooth C etc. After measurements had been achieved with

Figure 6.6: Photographs of the two types of rotary cutting instruments used in the loaded investigations a) diamond (Hi-Di 541) and b) tungsten carbide bur (Jet FG 57).

RCI 1 cutting all ten teeth, RCI 2 was inserted. The handpiece was then scanned whilst this second RCI was cutting tooth A, then B, then C, and so on.

This final test was carried out on one turbine (TA96CM, KaVo) with diamond instruments only (Ash Hi-Di 541), at a load of 100 g.

# CHAPTER 7

# RESULTS

## 7.1 Rotation velocities

Following each scan, the SLV software produced a graph displaying a frequency spectrum for the handpiece under investigation, an example of which can be seen in Figure 6.3. With this handpiece (KaVo 637C), the peak occurred at 7.35 ± 0.01 kHz. Using equation 6.1, the speed of rotation of the RCI could be calculated as 441,000 rpm. Equation 6.2 then enabled the conversion to SI units, and revealed that the handpiece was operating at 46,181 rad/s. These calculations were applied to all seven handpieces to derive maximum handpiece operating speeds (Table 7.1).

As the manufacturers of the handpieces had indicated approximate maximum rotation speeds of instruments in their literature, it was possible to compare these documented speeds with those that were achieved in the current study. Results of this comparison are included in Table 7.1 as a percentage difference (calculated using equation 6.3). A positive sign denotes that the derived speed was higher than the documented speed, and a negative sign indicated that the documented speed was greater.

## 7.2 Unloaded measurements

Vibration data were acquired for five turbines and two speed-increasing handpieces, whilst operated unloaded, with and without a rotary cutting instrument. Raw data for unloaded measurements can be found in Appendix 11.1. Observations of individual handpieces are recorded, followed by an overall analysis of statistical significance in section 7.2.8.

### 7.2.1 W&H - WA99A

All vibration displacement data from this handpiece were measured at less than 0.5 µm (Table 7.2). Although the presence or absence of a RCI had an effect on the results ($p < 0.01$), this was not consistent across the six scan points (Figure 7.1a). When equipped with a RCI, the vibration amplitude was higher at the base of the head (scan point 3, Figure 6.4) than all other areas ($p < 0.05$).

### 7.2.2 KaVo - 25CHC

When equipped with a RCI, the scan point nearest to the RCI (scan point 3, Figure 6.4) demonstrated the greatest extent of vibration (up to a maximum of 3.6 µm). Displacement here was significantly greater ($p < 0.01$) than points further from the rotating instrument (point 1 and 4-6). This trend was also apparent when the handpiece was not equipped with a RCI, in that the greatest vibrations were found near to the (vacant) insertion site of the RCI (Figure 7.1b), and points 1-3 all differed significantly from points 4-6 ($p < 0.05$). At each scan point, mean values were all greater with a RCI than without (Table 7.2); the overall effect of using a RCI with this speed-increasing handpiece was statistically significant ($p < 0.01$). It should be noted that this data, particularly in the presence of a RCI, was highly variable. For example, the mean of the maximum displacement amplitudes at the second scan point was 0.94 µm, but with a relatively large standard deviation of 1.26 µm.

### 7.2.3 W&H - TA98CM

Mean displacement amplitudes ranged from 0.09 to 0.26 µm with a RCI and from 0.11 to 0.27 µm without a RCI (Table 7.3). The presence or absence of RCI had no significant effect on the vibration of this turbine ($p = 0.33$). The six points selected for analysis (Figure 6.4) indicated a similar degree of vibration throughout the length of the handpiece, although

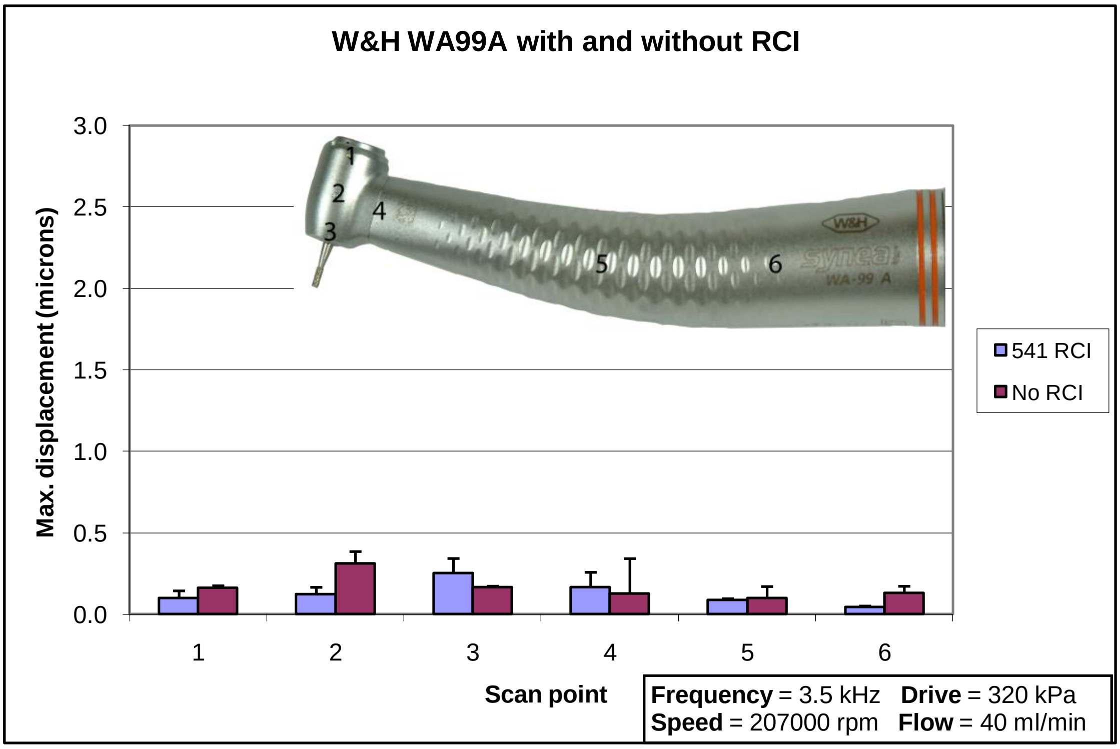
Table 7.1: Mean frequency of main peak and equivalent rate of instrument rotation whilst operated unloaded.

| Model | Measured frequency (kHz) | Calculated speed (krpm) | Calculated speed (rad/s) | Comparison with documented max. speed |
|---|---|---|---|---|
| WA99A | 3.45 | 207 | 21,677 | + 3.5% |
| 25CHC | 3.09 | 185 | 19,415 | - 7.5% |
| TA98CM | 5.78 | 347 | 36,317 | - 0.9% |
| 660C | 5.96 | 357 | 37,447 | + 2.0% |
| TA96CM | 6.21 | 372 | 39,018 | + 0.5% |
| 637C | 7.38 | 443 | 46,370 | - 7.7% |
| TA98M | 5.82 | 349 | 36,568 | - 0.3% |

Table 7.2: Vibration data (mean μm +/- 1 standard deviation) for speed-increasing handpieces whilst operated unloaded with and without a RCI.

| | W&H WA99A | | KaVo 25CHC | |
|---|---|---|---|---|
| **Scan point** | **With 541 RCI** | **With no RCI** | **With 541 RCI** | **With no RCI** |
| 1 | 0.10 ± 0.05 | 0.03 ± 0.02 | 0.37 ± 0.37 | 0.22 ± 0.10 |
| 2 | 0.12 ± 0.05 | 0.10 ± 0.07 | 0.94 ± 1.26 | 0.24 ± 0.16 |
| 3 | 0.25 ± 0.09 | 0.01 ± 0.01 | 1.33 ± 0.28 | 0.47 ± 0.10 |
| 4 | 0.16 ± 0.10 | 0.46 ± 0.22 | 0.32 ± 0.09 | 0.02 ± 0.01 |
| 5 | 0.09 ± 0.01 | 0.36 ± 0.07 | 0.08 ± 0.06 | 0.04 ± 0.02 |
| 6 | 0.04 ± 0.01 | 0.28 ± 0.04 | 0.06 ± 0.05 | 0.01 ± 0.01 |

a)



b)

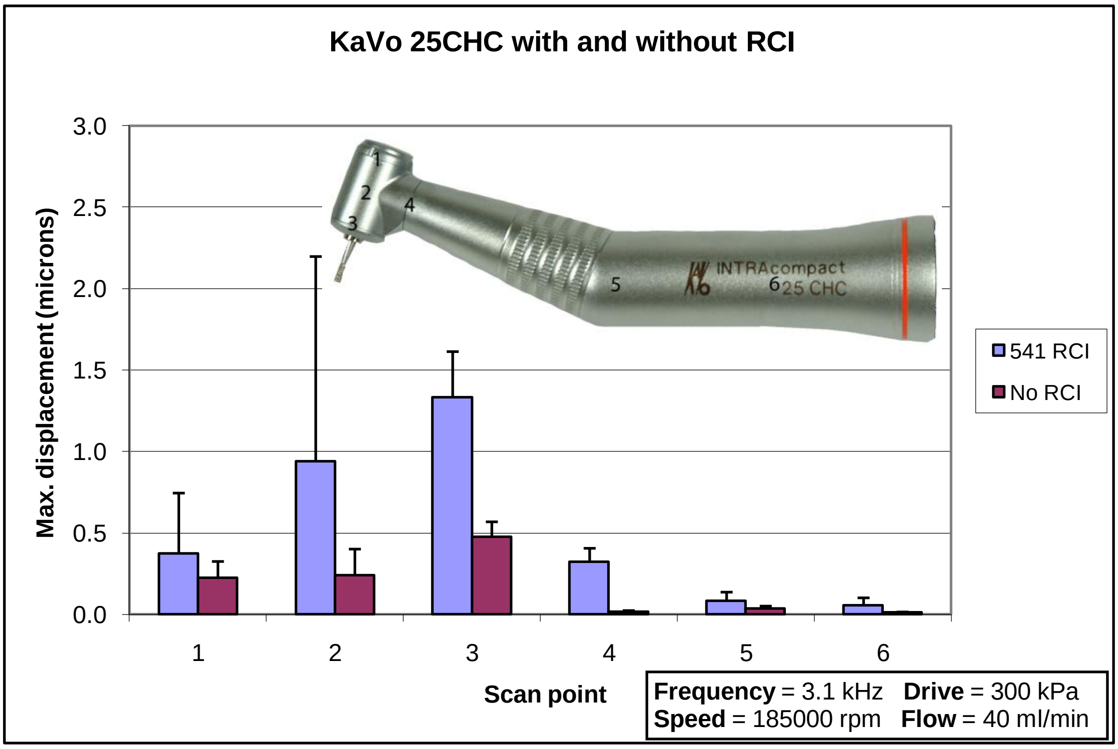


Figure 7.1: Maximum mean vibration displacement amplitude data from speed-increasing handpieces a) W&H WA99A and b) KaVo 25CHC. Error bars show +1 standard deviation. Handpiece illustrations indicate locations selected for scanning (ie scan points).

in contrast to other handpiece models, scan point 3 exhibited lower levels of vibration ($p < 0.05$) than other points (1, 2 and 6; Figure 7.2a).

### 7.2.4 KaVo - 660C

The largest mean vibration recorded both with (0.33 µm) and without a RCI (0.47 µm) was measured at scan point 1 on the top of the turbine head (Table 7.3), and was significantly greater than at all other points ($p < 0.01$). Amplitudes of vibrations tended to decrease at scan points further from the head (Figure 7.2b). The influence of the RCI was not significant ($p = 0.69$).

### 7.2.5 W&H - TA96CM

The maximum displacement recorded was 0.41 µm at scan point 4 (Table 7.4). The least vibration was detected at scan point 3 at the base of the head, particularly when no RCI was present (Figure 7.3a). The significant influence of the RCI ($p < 0.01$) led to the results for scan point 1 being greater than point 6 ($p < 0.01$), however no other scan points differed from one another ($p > 0.05$).

### 7.2.6 KaVo - 637C

The RCI had a significant effect ($p < 0.01$), and although vibration amplitudes were generally higher with a RCI than without, the reverse was true at scan point 2 (Figure 7.3b). Some scan points differed in the extent of vibration displayed ($p < 0.05$), but no obvious trends were observed. All data revealed vibrations lower than 0.5 µm (Table 7.4).

### 7.2.7 W&H - TA98M

Equipping this handpiece with a RCI influenced results ($p < 0.01$), but appeared to both increase and decrease vibrations depending on location (Figure 7.4). Some differences were observed between scan locations ($p < 0.01$), but followed no particular pattern. A relatively

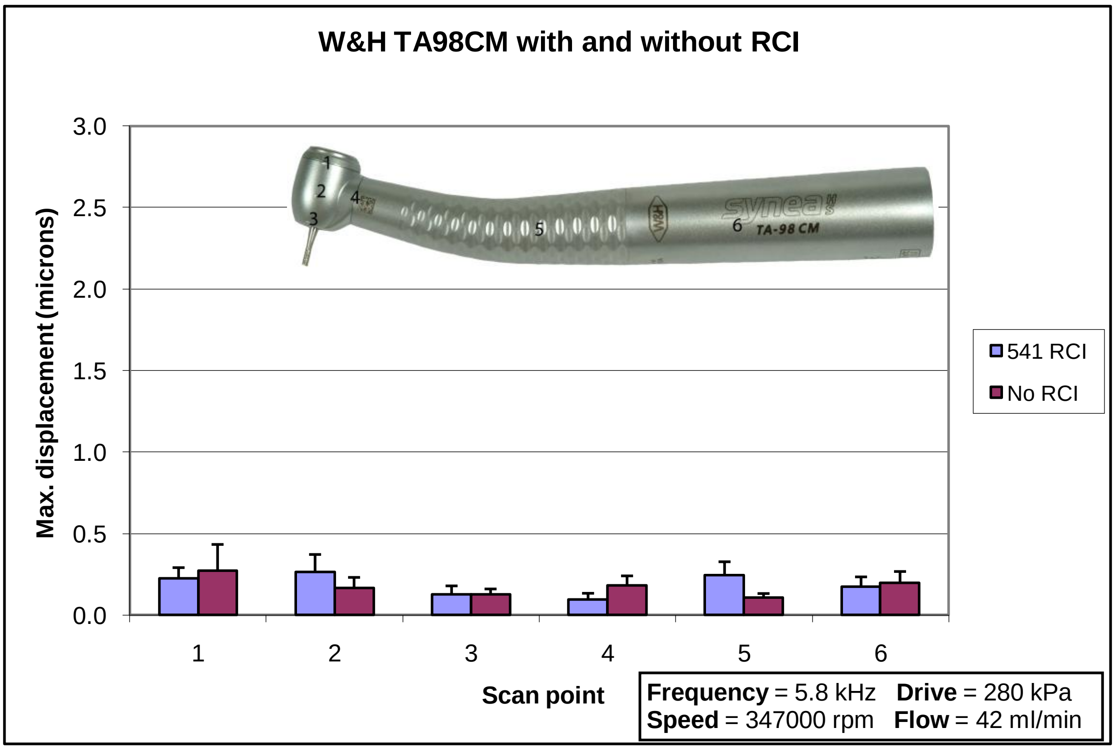
Table 7.3: Vibration data (mean μm +/- 1 standard deviation) for standard turbine handpieces (with ceramic bearings) whilst operated unloaded with and without a RCI.

| | **W&H TA98CM** | | **KaVo 660C** | |
|---|---|---|---|---|
| **Scan point** | **With 541 RCI** | **With no RCI** | **With 541 RCI** | **With no RCI** |
| 1 | 0.22 ± 0.07 | 0.27 ± 0.17 | 0.33 ± 0.07 | 0.47 ± 0.18 |
| 2 | 0.26 ± 0.11 | 0.16 ± 0.07 | 0.18 ± 0.03 | 0.20 ± 0.05 |
| 3 | 0.13 ± 0.05 | 0.13 ± 0.04 | 0.15 ± 0.04 | 0.21 ± 0.07 |
| 4 | 0.09 ± 0.04 | 0.18 ± 0.06 | 0.13 ± 0.10 | 0.07 ± 0.01 |
| 5 | 0.24 ± 0.09 | 0.11 ± 0.03 | 0.08 ± 0.03 | 0.08 ± 0.02 |
| 6 | 0.17 ± 0.06 | 0.20 ± 0.07 | 0.17 ± 0.04 | 0.04 ± 0.01 |

Table 7.4: Vibration data (mean μm +/- 1 standard deviation) for turbine handpieces with small head whilst operated unloaded with and without a RCI.

| | **W&H TA96CM** | | **KaVo 637C** | |
|---|---|---|---|---|
| **Scan point** | **With 541 RCI** | **With no RCI** | **With 541 RCI** | **With no RCI** |
| 1 | 0.16 ± 0.04 | 0.18 ± 0.07 | 0.36 ± 0.07 | 0.16 ± 0.05 |
| 2 | 0.18 ± 0.06 | 0.06 ± 0.03 | 0.15 ± 0.06 | 0.31 ± 0.07 |
| 3 | 0.09 ± 0.02 | 0.19 ± 0.05 | 0.16 ± 0.06 | 0.16 ± 0.05 |
| 4 | 0.12 ± 0.04 | 0.19 ± 0.10 | 0.19 ± 0.05 | 0.12 ± 0.04 |
| 5 | 0.21 ± 0.06 | 0.10 ± 0.04 | 0.27 ± 0.12 | 0.10 ± 0.02 |
| 6 | 0.15 ± 0.05 | 0.02 ± 0.02 | 0.14 ± 0.04 | 0.13 ± 0.06 |

a)



b)

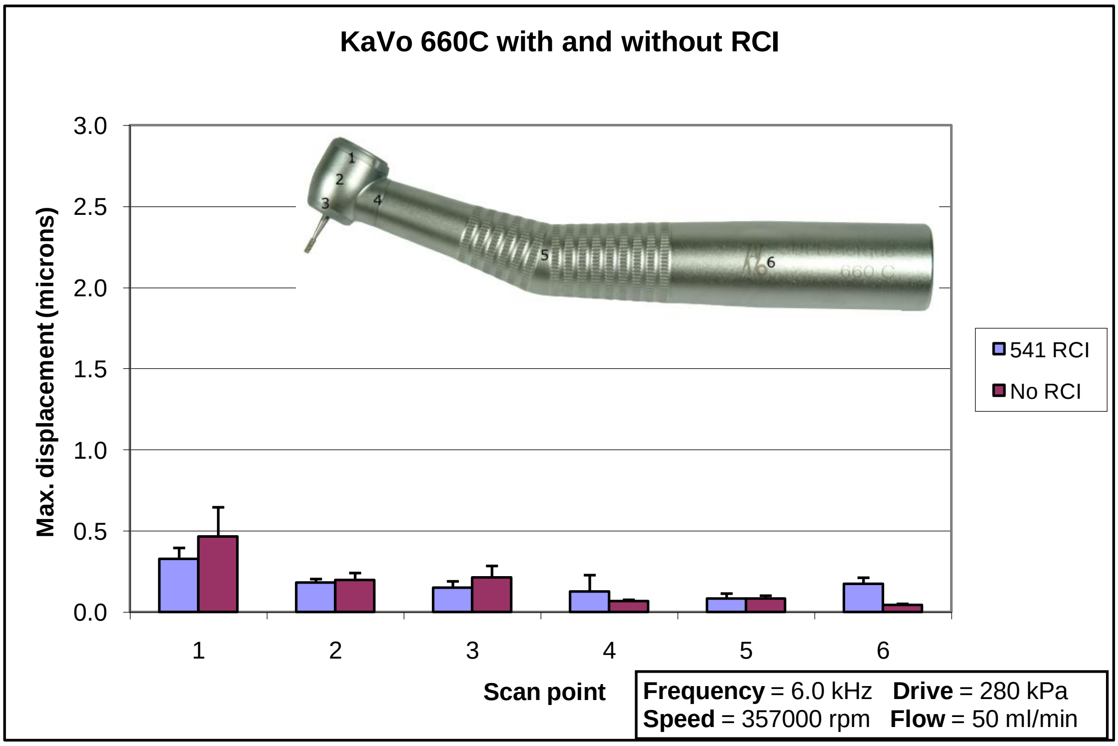
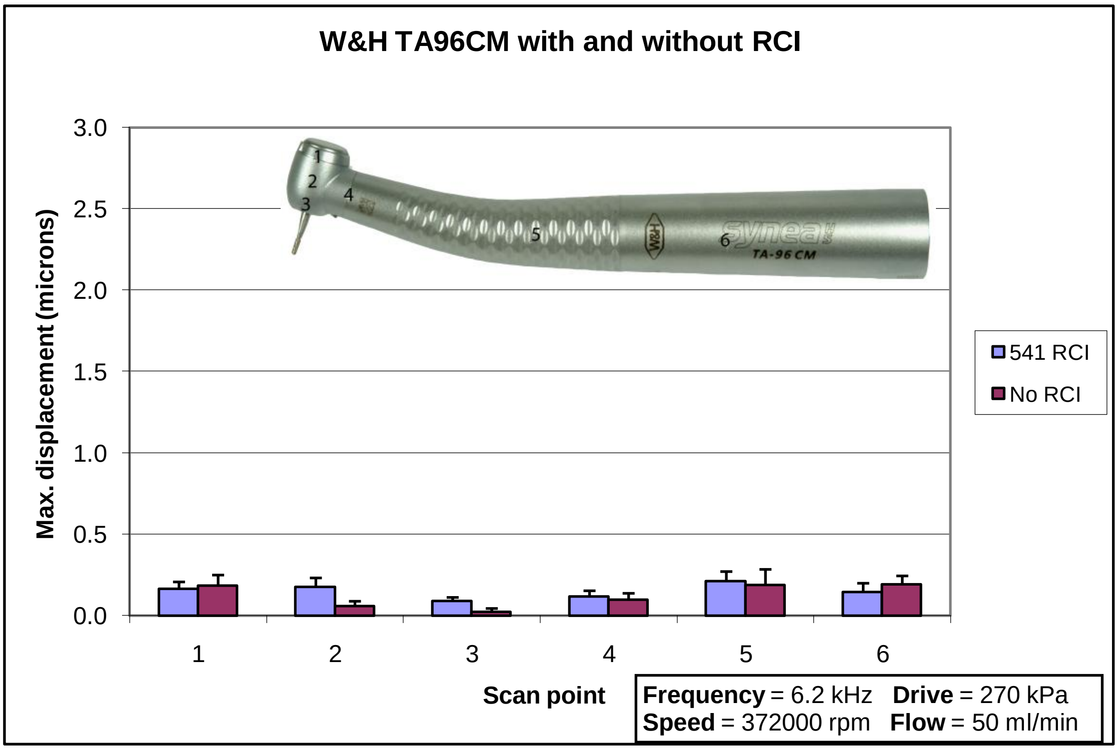


Figure 7.2: Maximum mean vibration displacement amplitude data from standard turbines with ceramic bearings a) W&H TA98CM and b) KaVo 660C. Error bars show +1 standard deviation. Handpiece illustrations indicate locations selected for scanning (ie scan points).

a)



b)

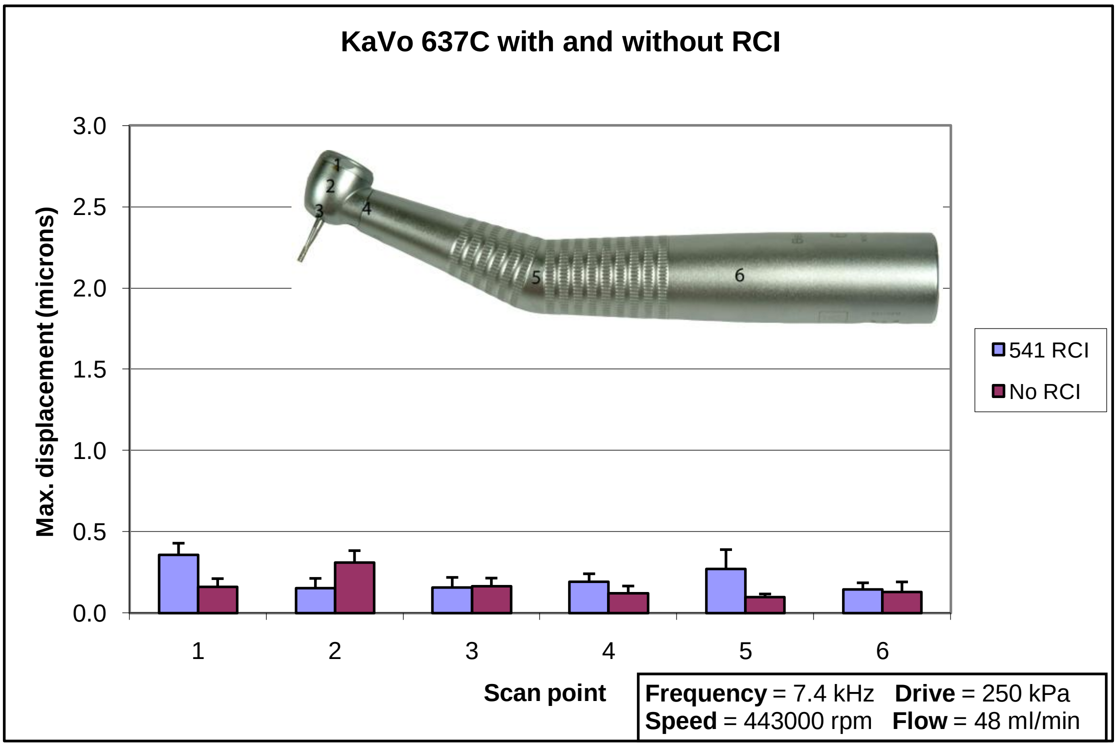


Figure 7.3: Maximum mean vibration displacement amplitude data from turbines with small head a) W&H TA96CM and b) KaVo 637C. Error bars show +1 standard deviation. Handpiece illustrations indicate locations selected for scanning (ie scan points).

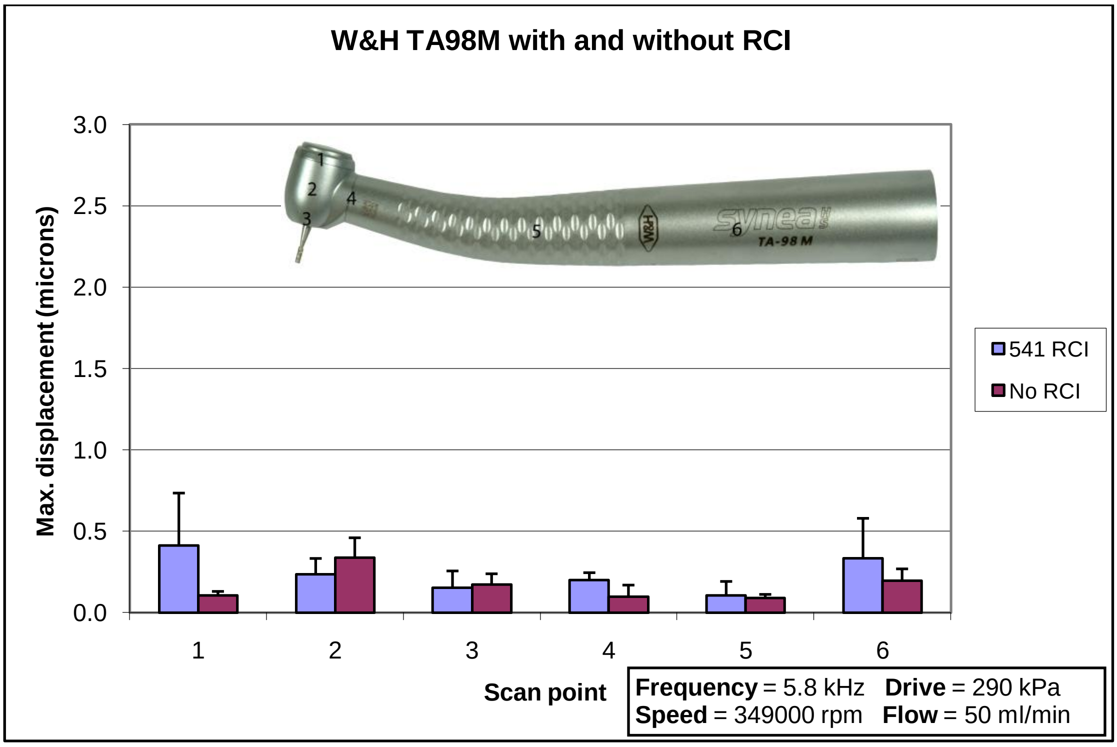


Figure 7.4: Maximum mean vibration displacement amplitude data from turbine with steel bearings W&H TA98M. Error bars show +1 standard deviation. Handpiece illustration indicates locations selected for scanning (ie scan points).

high mean level of vibration (0.34 µm) was also observed at scan point 6, furthest from the handpiece head (Table 7.5).

### 7.2.8 Statistical analysis of unloaded results

At a significance level of $p = 0.05$, a univariate ANOVA test (Table 7.6) showed that there were significant differences between handpiece models ($p < 0.01$). The presence or absence of a RCI also produced a significant effect ($p < 0.01$), and there were significant differences between the points selected for measurement along the side of the handpiece ($p < 0.01$).

In an investigation of the homogeneity of variance, Levene's test indicated that the error variance of the dependent variable was not equal across the groups ($p < 0.01$). As the data therefore did not satisfy the assumptions of a parametric test, the most appropriate of the post hoc tests available was the Games-Howell, which is suitable for use even when population variances differ.

The post hoc Games-Howell tests revealed that only two models of handpiece differed from the others in relation to the extent of vibration. The KaVo 25CHC speed-increasing handpiece generated significantly greater vibrations than five other models ($p < 0.01$). However vibration displacement amplitudes recorded for the W&H TA-96CM turbine (with small head) were significantly smaller than four other models ($p < 0.01$). The RCI influenced vibrations by increasing vibration levels compared to those measured when no RCI was inserted ($p < 0.01$). Scan points along the head of the handpiece (points 1, 2 and 3) were each found to exhibit greater vibrations than each of the scan points (5, 6 and 7) along the handpiece body ($p < 0.01$), particularly when an RCI was present (Figure 7.5).

Table 7.5: Vibration data (mean µm +/- 1 standard deviation) for standard turbine handpiece (with steel bearings) whilst operated unloaded with and without a RCI.

| | W&H TA98M | |
|---|---|---|
| **Scan point** | **With 541 RCI** | **With no RCI** |
| 1 | 0.41 ± 0.32 | 0.10 ± 0.03 |
| 2 | 0.24 ± 0.10 | 0.34 ± 0.12 |
| 3 | 0.15 ± 0.11 | 0.17 ± 0.07 |
| 4 | 0.20 ± 0.05 | 0.10 ± 0.07 |
| 5 | 0.11 ± 0.09 | 0.09 ± 0.02 |
| 6 | 0.34 ± 0.24 | 0.20 ± 0.07 |

Table 7.6: Main ANOVA results for unloaded measurements, generated using SPSS software. Significance levels are less than 0.05, indicating that all independent variables (model, scan point and RCI) had an effect on the dependent variable (ie vibration displacement amplitude). Post hoc testing was necessary to establish what these effects were.

**Tests of Between-Subjects Effects**

Dependent Variable: Displacement (microns)

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Corrected Model | 28.060[a] | 83 | .338 | 11.832 | .000 |
| Intercept | 33.422 | 1 | 33.422 | 1169.724 | .000 |
| Model | 3.150 | 6 | .525 | 18.376 | .000 |
| ScanPoint | 2.103 | 5 | .421 | 14.721 | .000 |
| RCI | .793 | 1 | .793 | 27.770 | .000 |
| Model * ScanPoint | 12.801 | 30 | .427 | 14.934 | .000 |
| Model * RCI | 3.358 | 6 | .560 | 19.588 | .000 |
| ScanPoint * RCI | .460 | 5 | .092 | 3.219 | .007 |
| Model * ScanPoint * RCI | 5.394 | 30 | .180 | 6.293 | .000 |
| Error | 21.601 | 756 | .029 | | |
| Total | 83.082 | 840 | | | |
| Corrected Total | 49.660 | 839 | | | |

a. R Squared = .565 (Adjusted R Squared = .517)

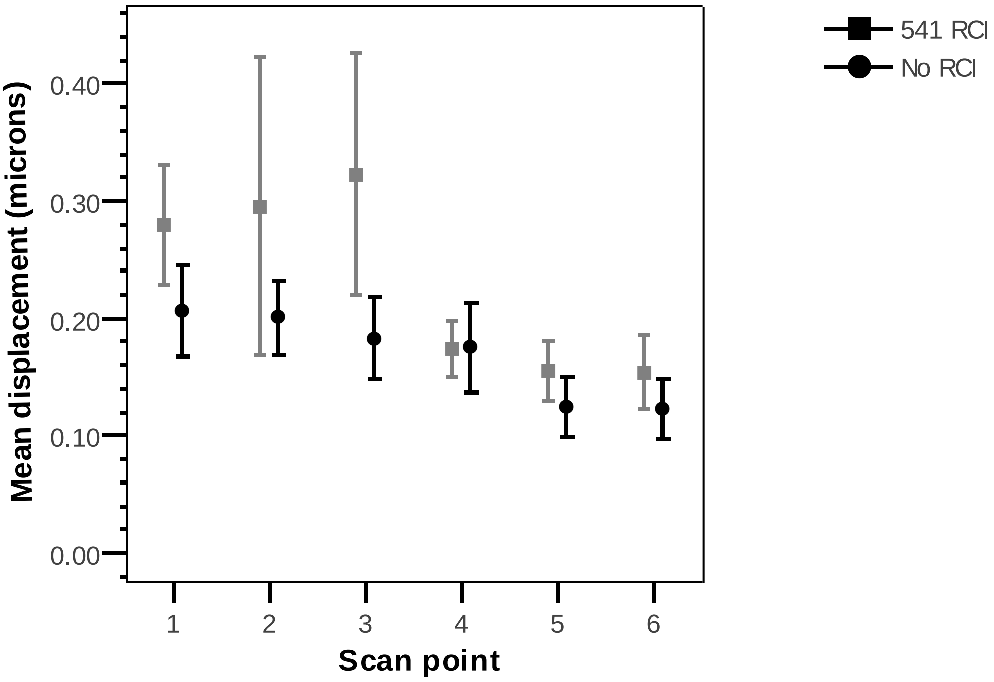


Figure 7.5: Influence of the presence or absence of a rotary cutting instrument (Ash Hi-Di 541 diamond RCI) on vibration displacement amplitudes. Error bars show 95% confidence intervals of the means. Scan points 1-3 are at the head of the handpiece, and show higher levels of vibration than scan points 4-6 along the handpiece body.

## 7.3 Loaded measurements

The vibrations of three turbines were measured at scan point 2 (Figure 6.4) whilst cutting under loads of 50 to 200 g. Raw data from loaded measurements can be found in Appendix 11.2. The overall analysis of statistical significance is included in section 7.3.4, following some descriptive results for each handpiece.

### 7.3.1 W&H - TA98CM

There was a large extent of variability between measurements when the tungsten carbide RCI was loaded with a force of 50 g, with data ranging from 0.25 to 2.26 µm, despite being taken from the same scan point (Figure 7.6b). The mean vibration displacement of the turbine when equipped with this bur was significantly higher at 50g than at higher loads ($p < 0.05$), where the data was more consistently distributed. Mean displacements were lower with a diamond RCI than with a tungsten carbide RCI ($p < 0.01$), which was observed at all of the measured loads (Table 7.7a).

### 7.3.2 KaVo - 660C

Although there were significant differences between the RCIs ($p < 0.01$), there were no obvious patterns relating to the interaction between RCI and loading (Figure 7.6). A load of 200 g when using a diamond RCI resulted in significantly lower vibrations than at smaller loads ($p < 0.05$). The greatest variability of vibration results for this handpiece occurred when the diamond RCI was loaded with a force of 50 g; at the same load the standard deviation of the tungsten carbide bur data was much lower (Table 7.7b).

### 7.3.3 W&H - TA96CM

When equipped with a diamond RCI, a pattern of increasing vibration as the load increased was observed, although this pattern was less defined when a tungsten carbide RCI was used (Figure 7.6). A load of 50 g produced significantly lower vibration displacement amplitudes than at higher loads ($p < 0.01$). Mean vibration amplitudes under all conditions were less than 0.50 µm (Table 7.7c). The influence of the RCI was significant ($p < 0.01$); at loads above 50 g, mean vibrations were higher with a diamond RCI than with a tungsten carbide bur.

### 7.3.4 Statistical analysis of loaded results

The results of the univariate ANOVA test revealed significant differences in the vibrations of each handpiece ($p = 0.001$), and between each of the four loads selected for the investigation ($p = 0.001$). When analysing the overall effect of the type of cutting instrument (diamond or tungsten carbide), there appeared to be no significant difference in vibration displacement amplitudes ($p = 0.463$). However the interaction between handpiece and RCI was significant ($p < 0.01$), which is consistent with the results of the individual analyses described in sections 7.3.1 to 7.3.3. Equipping a TA98CM turbine with a diamond RCI resulted in smaller vibrations than when a tungsten carbide RCI was used; the opposite was true for the two other turbines (ie using the diamond RCI produced larger vibrations than those seen with the tungsten carbide RCI).

As for the unloaded data, Levene's test showed that the error variance across groups was not homogeneous ($p < 0.01$), indicating that the data was not parametrically distributed. With all handpiece and instrument data pooled, Games-Howell tests demonstrated that the only

Table 7.7: Vibration data (mean µm +/- 1 standard deviation) whilst operated at increasing loads with 541 diamond RCI or tungsten carbide RCI. Handpieces under investigation were a) TA98CM, b) 660C and c) TA96CM.

a)

| | **TA98CM** | |
|---|---|---|
| **Load (g)** | **541 RCI** | **TC RCI** |
| 50 | 0.10 ± 0.11 | 1.29 ± 0.77 |
| 100 | 0.15 ± 0.10 | 0.31 ± 0.19 |
| 150 | 0.31 ± 0.05 | 0.35 ± 0.16 |
| 200 | 0.20 ± 0.09 | 0.44 ± 0.18 |

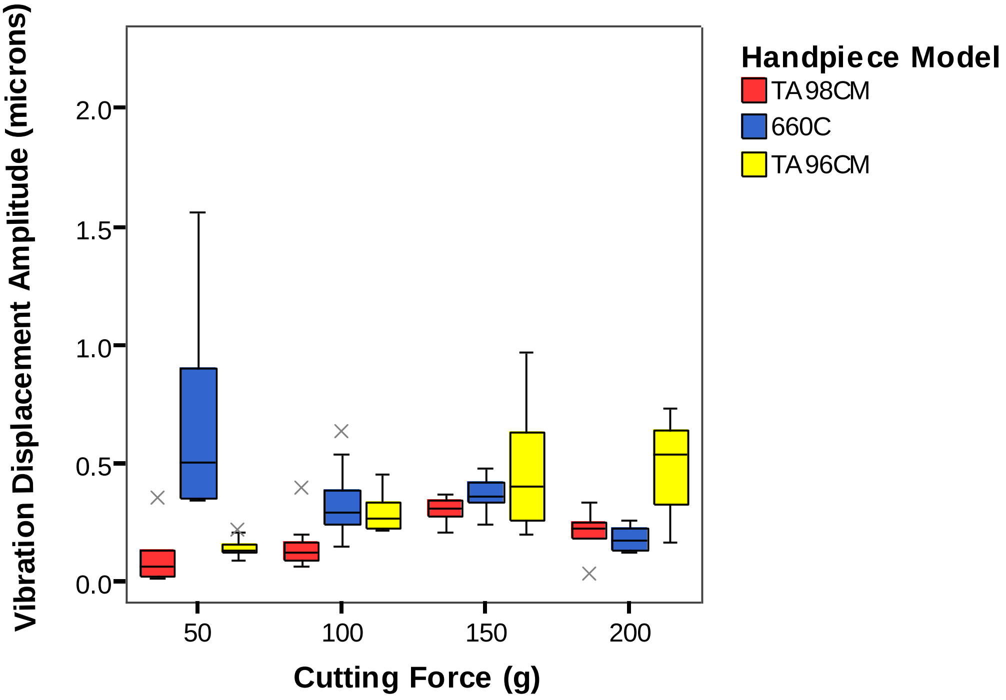
b)

| | **660C** | |
|---|---|---|
| **Load (g)** | **541 RCI** | **TC RCI** |
| 50 | 0.67 ± 0.42 | 0.14 ± 0.03 |
| 100 | 0.33 ± 0.15 | 0.22 ± 0.07 |
| 150 | 0.37 ± 0.07 | 0.19 ± 0.04 |
| 200 | 0.18 ± 0.05 | 0.23 ± 0.06 |

c)

| | **TA96CM** | |
|---|---|---|
| **Load (g)** | **541 RCI** | **TC RCI** |
| 50 | 0.15 ± 0.04 | 0.29 ± 0.04 |
| 100 | 0.30 ± 0.09 | 0.16 ± 0.12 |
| 150 | 0.46 ± 0.25 | 0.38 ± 0.20 |
| 200 | 0.49 ± 0.20 | 0.17 ± 0.10 |

a)



b)

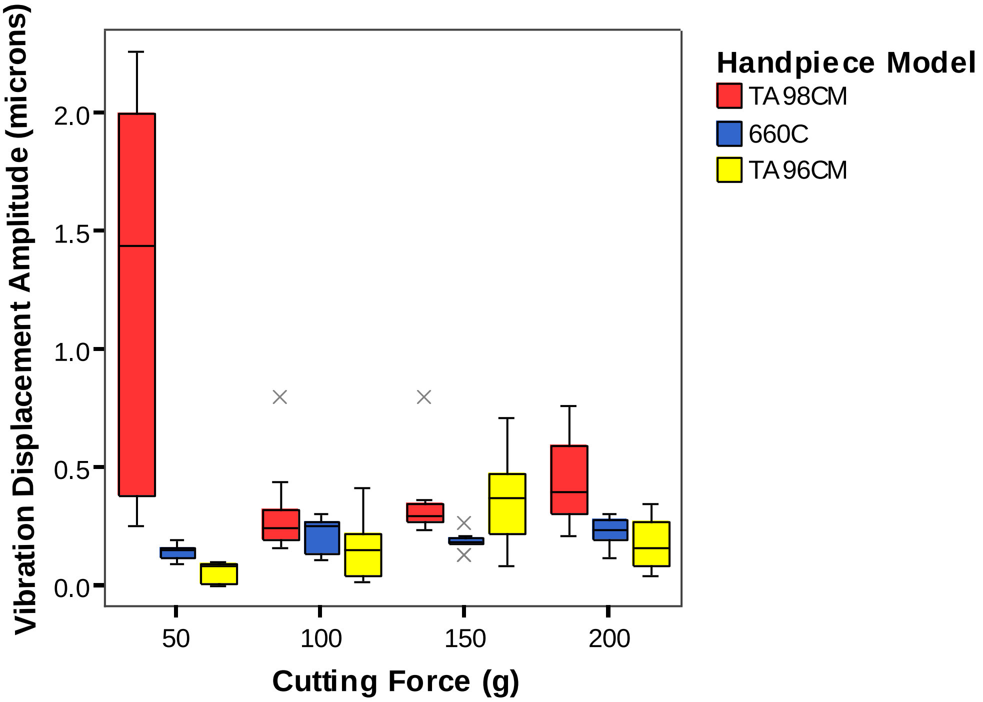


Figure 7.6: Boxplots for three turbine models equipped with a) diamond RCI or b) tungsten carbide bur at four increasing loads. Crosses indicate outliers.

significant difference between loads occurred between 100 and 150 g (p = 0.004), with more vibration occurring under the higher loading.

Although the ANOVA results implied differences between the handpieces (when loaded), not all of the post hoc comparisons confirmed that these differences were significant. A post hoc Tukey test, for example, indicated that each of the three handpieces differed significantly from one another except the 660C and the TA96CM. However the Tukey test assumes that population variances are similar – an incorrect assumption in this study, as already revealed by Levene's test. This is why a Games-Howell test is more appropriate under these conditions, as this procedure was specifically designed for situations in which population variances differ[183]. The Games-Howell results showed no significant differences between handpieces whilst cutting under load, and therefore this must be the more reliable conclusion.

## 7.4 Tooth/RCI exchange

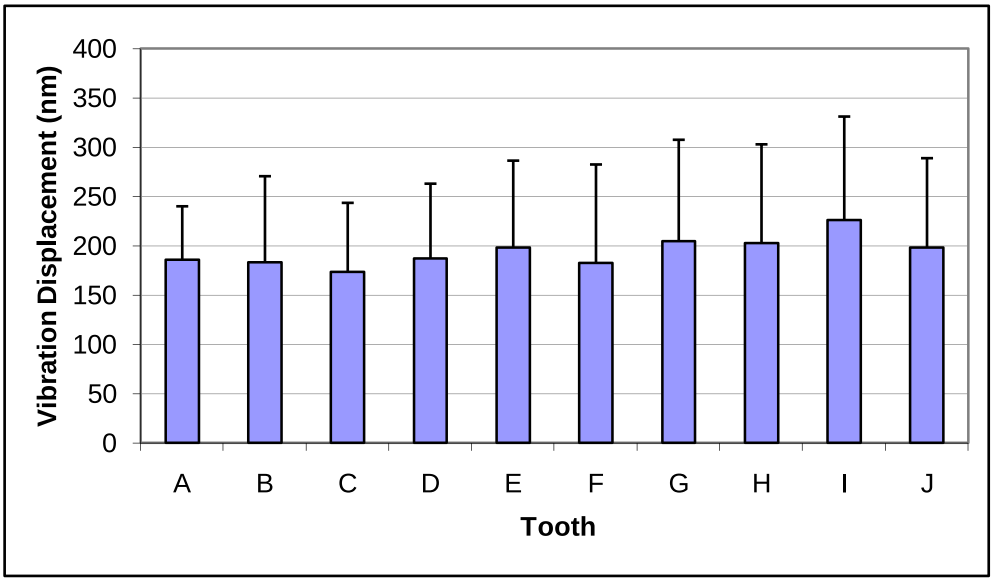
An investigation into the differences in handpiece vibration as a consequence of changing individual teeth, and also as a result of changing RCIs, was carried out whilst cutting at a load of 100 g.

An initial inspection of the graph comparing the teeth used for this study, revealed consistent levels of vibration across the ten teeth (Figure 7.7a). This suggested that any differences between the teeth did not affect the vibration displacement amplitudes. The mean values for each tooth ranged from 173.15 ± 70.53 nm to 226.12 ± 105.11 nm (Table 7.8).

Table 7.8: Vibration data (nm) for TA96CM turbine whilst cutting into ten teeth at a load of 100g, using ten identical rotary cutting instruments (RCI).

| | | Tooth | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | G | H | I | J | Mean | SD |
| RCI | 1 | 145.1 | 153.0 | 198.6 | 139.5 | 186.4 | 112.5 | 234.4 | 123.6 | 153.0 | 88.8 | 153.49 | 43.06 |
| | 2 | 151.9 | 264.7 | 115.5 | 271.2 | 165.5 | 160.5 | 236.4 | 235.9 | 111.5 | 122.3 | 183.54 | 62.57 |
| | 3 | 183.5 | 262.0 | 268.0 | 236.2 | 189.0 | 223.6 | 150.1 | 314.3 | 194.8 | 202.1 | 222.36 | 48.67 |
| | 4 | 219.8 | 82.6 | 53.1 | 58.8 | 75.7 | 50.8 | 68.3 | 85.9 | 59.8 | 42.4 | 79.71 | 51.19 |
| | 5 | 140.8 | 161.5 | 76.5 | 153.7 | 272.0 | 88.6 | 88.4 | 80.7 | 365.4 | 343.2 | 177.07 | 110.20 |
| | 6 | 216.9 | 160.2 | 162.3 | 305.2 | 205.9 | 196.9 | 221.6 | 178.6 | 277.6 | 224.6 | 214.98 | 46.80 |
| | 7 | 164.7 | 80.3 | 185.6 | 118.3 | 83.9 | 95.8 | 236.7 | 100.0 | 337.7 | 233.4 | 163.63 | 84.99 |
| | 8 | 169.5 | 148.9 | 226.1 | 189.6 | 378.0 | 363.3 | 153.0 | 270.8 | 215.8 | 200.2 | 231.52 | 81.80 |
| | 9 | 318.2 | 153.9 | 226.7 | 243.6 | 178.0 | 237.8 | 438.5 | 322.2 | 354.5 | 241.1 | 271.45 | 86.25 |
| | 10 | 146.5 | 361.8 | 219.1 | 151.9 | 248.1 | 297.2 | 217.4 | 314.0 | 191.1 | 284.0 | 243.11 | 70.97 |
| | Mean | 185.69 | 182.89 | 173.15 | 186.80 | 198.25 | 182.69 | 204.47 | 202.60 | 226.12 | 198.22 | | |
| | SD | 54.51 | 87.82 | 70.53 | 76.34 | 88.25 | 99.94 | 103.18 | 100.43 | 105.11 | 90.78 | | |

a)



b)

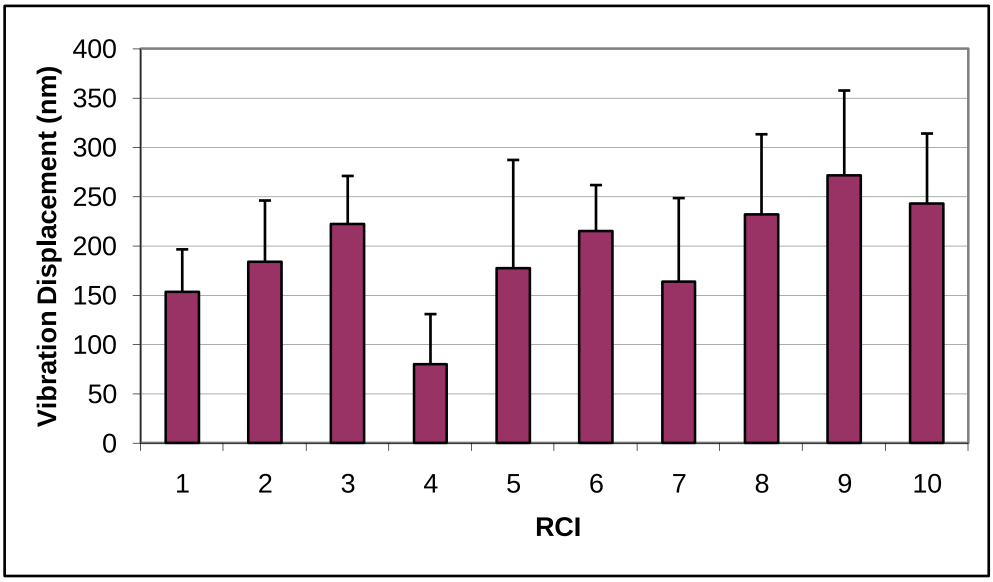


Figure 7.7: Mean vibration displacement amplitude data from TA96CM recorded under 100 g load and presented according to a) tooth and b) RCI.

The variation between the mean results of the individual instruments was more apparent than the variation between teeth (Figure 7.7b), with values ranging from 79.71 ± 51.19 nm to 271.45 ± 86.25 nm (Table 7.8).

### 7.4.1 Statistical analysis of tooth/RCI exchange results

When a one-way univariate ANOVA was performed to compare the ten teeth, Levene's test showed that the variances of the groups were equal ($p = 0.562$). The ANOVA produced a significance of $p = 0.976$, therefore there were no significant differences in vibration levels recorded between the ten teeth.

However the variances between the RCIs were found to differ ($p = 0.012$), violating one of the assumptions of the ANOVA test, and requiring instead the application of Welch's *F*-ratio. This revealed significant differences in the vibration displacement amplitudes of the handpieces when equipped with the ten different instruments ($p < 0.01$). Using a post hoc Games-Howell test, it was possible to see that most of the RCIs had produced similar vibration displacement amplitudes, but that one in particular (RCI 4, figure 7.7b) was associated with significantly smaller vibrations than six other RCIs.

# CHAPTER 8

# DISCUSSION

## 8.1 SLV methodology

It has been demonstrated that detection and measurement of high-speed dental handpiece vibration can be achieved using a scanning laser vibrometer. Laser Doppler vibrometers have been used to measure vibrations in various fields including engineering and the automotive industry, biology and medicine[145]. Topics are diverse - from the investigation of vibrations inside butterfly ears[184], to detection of damage in aircraft[185] or defects in works of art[186]. As these vibrometers are non-contact and non-invasive, they are able to record vibrations of very small structures such as Micro-Electro Mechanical Systems (MEMS)[145]. They avoid the problem of mass-loading, which is a recognised limitation of more traditional vibration detectors (eg accelerometers) when attached to small or light objects[148]. For this reason in particular, the SLV is useful in the assessment of vibrating or oscillating dental instruments.

Laser vibrometers are able to detect vibration displacement amplitudes at a resolution of 2 nm or less[187]. Earlier publications and previous calibration of the particular SLV used in this study demonstrated that it is capable of producing highly reproducible, accurate results[152, 188]. It was also important that the equipment had the capacity to discern vibrations at high frequencies, as the handpieces were operating at up to 7.38 kHz when unloaded (Table 7.1). This is well within the measurement range of up to 1.5 MHz of the PSV-300-F/S High Frequency SLV[189]. Finally, in the loaded studies it was crucial that measurements should be recorded within a few seconds, as the instruments cut through the dental enamel very quickly. The SLV was well suited to the requirements of this study of high-speed handpiece vibration due to its non-contact nature, high resolution at high frequencies, and capacity for rapid detection.

## 8.2 Rotation velocities

The maximum instrument rotation speeds for each handpiece, as documented by the corresponding manufacturer, are detailed in Table 6.1. Using the SLV it was possible to determine the fundamental frequency of each unloaded handpiece, and from this derive the speed of instrument rotation. The results of these calculations were described in Table 7.1.

When documented maximum speeds were compared with measured maximum speeds, it was found that five of the seven handpieces had differences no greater than +/- 3.5%. These small differences could be attributed to small changes in drive air pressures, which are known to affect rotation speeds[132]. The other two handpieces (KaVo's 25CHC and 637C models) were operating a little more slowly than the expected maximum at a difference of almost 8%. It should be noted that the maximum speed documented in the accompanying literature for the 637C turbine was actually given as 400 to 480 krpm. The speed derived by measurement and calculation (at 443 krpm) fell within this range.

However the result for the 25CHC model is surprising. This was the KaVo speed-increasing handpiece, powered by an electric motor that was programmed to run at 40 krpm. As the handpiece gear ratio was 1:5, the instrument should have rotated five times faster than the motor, at 200 krpm. It is not known why the measured rate was only 185 krpm. The discrepancy is likely to be attributed to either the measurement technique or to inaccuracies in the dental equipment. The method of calculating speeds based on the SLV frequency peak appeared to produce accurate data for most of the handpieces, but could be compared with an alternative method such as that described by Darvell and Dyson[2]. This provides an avenue for further research.

## 8.3 Unloaded measurements

The ten scans carried out under each condition (ie with or without RCI) did not always give consistent results, despite no changes being introduced to the experimental set-up between the scans. The greatest variation in recordings occurred under the same conditions that also exhibited the largest vibrations.

In clinical dentistry a handpiece is never operated without a RCI. The reason that this condition was investigated in this *in vitro* study was to provide baseline data prior to testing with different types of RCIs. Initial examination of the results of the statistical analyses indicated that equipping handpieces with a RCI increased vibrations, particularly at the head end of the handpiece (scan points 1-3) where increases of 23 to 46% were observed (Figure 7.5). Unless an RCI was perfectly balanced in its shape and weight distribution, it would be expected to rotate in a slightly eccentric manner[19], and therefore the increase in vibrations at the head end of the handpiece would have been anticipated.

Statistical differences were found between some of the unloaded handpieces, which is similar to the conclusion drawn by Shah *et al.*[146] in their study of sonic scaler vibration. Data had been pooled for the seven handpiece models when the statistical analyses were carried out to establish the overall influence of the RCI and scan point positions. As the 25CHC speed-increasing handpiece had generated much larger vibrations than other models, the data from this handpiece is likely to have contributed a disproportionate amount to the overall effects observed. When the 25CHC data was excluded and the ANOVA was repeated, the presence of a RCI still resulted in significantly greater vibrations than when no RCI was used ($p = 0.04$), and scan point data remained significantly different ($p < 0.01$). The largest vibrations were still found at the head end, although closer to the top of the head (scan point 1, Figure 6.4) rather than next to the insertion site of the RCI.

Previous publications have suggested that an advantage of using speed-increasing handpieces (in preference to turbines) is that they offer reduced levels of vibration[127, 128]. This was not substantiated by the present study. In fact, the overall mean vibration displacement of the speed-increasing handpieces was significantly larger than that of the turbines ($p < 0.01$). But, as described in section 7.2.9, the vibration of one of the two speed-increasing handpieces did not differ significantly from most of the turbines. Therefore it is recommended that the vibrations of each model should be evaluated individually, rather than generalising according to handpiece type.

It should be noted that even the greatest vibration amplitudes measured in this investigation remained below 4 μm – smaller than the width of an enamel prism[19]. In assessing the likelihood of vibrating tools contributing to the occupational disease hand-arm vibration syndrome (HAVS), the frequency, magnitude, duration of exposure, and cumulative exposure are taken into account[180]. The measured vibration is frequency-weighted to model the human response to vibration, although this relies on assumptions and there are doubts about the appropriateness of this technique[10]. The ISO guidance[180] describes how the frequency weighting should be applied, but the specified frequency range is limited to a maximum of 1000 Hz. The high-speed handpieces in the current study were operating at frequencies of 3.09 ± 0.01 to 7.38 ± 0.01 kHz (Table 7.1). Without accurate details of the durations that dental personnel are exposed to the vibration of these tools, it is not possible to apply these calculations to achieve a reliable risk assessment.

Although the use of rotary instruments has been linked to cracking of dental enamel[6, 19, 164], it is not known how much vibration is required to cause (or exacerbate) these effects. As the vibration amplitudes of the handpieces in the current study were small, it is proposed that they are unlikely to contribute to undesirable effects such as enamel cracking or HAVS, but further research into both of these conditions would enable a more definitive conclusion to be reached.

## 8.4 Loaded measurements

Like the unloaded measurements, the data collected displayed considerable variability when scans were repeated under identical conditions. Vibration levels were again small, with a maximum recorded amplitude of less than 2.3 µm. It was concluded that there were no significant differences in vibration displacement amplitudes between the handpiece models when loaded.

Due to the interactions of many parameters affecting handpiece performance[12, 134], it was necessary to standardise as many conditions as possible for these experiments. For this reason, static loads were applied, the magnitude of which were representative of those measured under clinical conditions[140, 142]. However in practice these loads are not constant – handpieces are held freely and intermittent pressure is applied by the operator, with loading depending on the tissue or material being cut, the stage of cavity preparation and the operator technique[125, 139]. The angle of attack of the RCI and direction of cutting would also vary. A better understanding of handpiece vibration would be achieved if clinical conditions could be more closely simulated.

An interesting finding of this part of the investigation was that handpiece vibrations differ depending on the extent of loading. This was particularly evident between the loads of 100 and 150 g, where the increase in load resulted in a statistically significant increase in mean vibration displacement amplitude ($p < 0.01$). As these are representative of the loads being applied by dentists in practice[140, 142], there may be justification for adapting operative technique if any future conclusive evidence proves that these small vibrations have adverse effects upon the dental tissues, operator or patient.

Also of interest is the discovery that the type of RCI has a significant effect on vibration of the handpiece depending on the handpiece model under investigation. This may appear to contradict the earlier conclusion that there were no differences between loaded handpieces. However the key consideration here is the *interaction* of the independent variables. In order to comprehend this phenomenon, an analogy could be used. Consider the following fictional scenario.

> A study is conducted into whether gender has an effect on height of children, and any other factors that may be related. A group of 100 children of the same age

> are measured – 50 boys and 50 girls, and no significant difference is found in height depending on gender. Then the same group are further investigated to look at whether being left handed or right handed corresponds to differences in height of the boys and girls. It is found that the 25 left handed girls are significantly taller than the 25 right handed girls. But the opposite is true for the boys – the 25 right handed boys are significantly taller than the 25 left handed boys. Therefore there are significant differences in height between left and right handers, but the *direction* of this effect is dependent upon gender. A variable that earlier appeared to have no significance (ie gender), has now become significant when analysed in the context of another variable (handedness).

Likewise, the handpiece model – initially thought to make no significant difference to vibration – was found in the loaded handpiece study to contribute to differences in levels of vibration when examined in relation to the cutting instrument used. For one of the turbines, a tungsten carbide RCI produced higher levels of vibration than a diamond RCI ($p < 0.01$). An opposite effect was found in the other two turbines – the diamond RCI was associated with the greater displacement amplitudes ($p < 0.01$). Ercoli *et al.*[126] also noted complex interactions between handpiece type (turbine or speed-increasing) and RCI type (diamond or tungsten carbide); the depth of material cut had an additional influence. These interactions may have implications for other cutting studies.

## 8.5 Tooth/RCI exchange

Because cutting instruments become worn during use[19], each new instrument was used to cut into a tooth no more than 20 times (each cut requiring less than five seconds) before being discarded. The number of times each extracted tooth could be cut was also limited by the volume of enamel available, meaning that it was only possible to achieve around ten successful scans per tooth. In the investigation of increasing loads, both tooth and instrument had been replaced at the same time. The third part of this study attempted to correct this error in experimental design, by investigating whether it was likely that the instrument, or the tooth, had a greater influence on handpiece vibration.

One factor to consider in cutting studies is the substrate. It could be argued that the material used for this purpose should be homogenous, so that inconsistencies in texture do not affect the vibration studies. But dental tissues have a complex anisotropic construction, and no substrate has been found that adequately substitutes for them[2, 134]. Another alternative employed by some researchers[140, 190] has been to use bovine teeth, but these were not recommended as they differ in structure from human teeth[19]. For these reasons real extracted human molar teeth were chosen for these investigations.

It had been anticipated that enamel sourced from a number of teeth might influence results, for example due to variation in age[19]. No significant differences were found between the different teeth whilst measuring handpiece vibrations ($p = 0.562$). This was an encouraging finding, as it indicated that any differences found in the loading study were not likely to be attributable to the use of different teeth. However it should be noted that only ten teeth were used for this comparison, and a greater number would provide a more reliable basis for this conclusion.

The individual cutting instruments used in this investigation were found to differ significantly (p = 0.012). Watson and Cook[19] observed differences in the concentricity of bur rotation depending upon construction (tungsten carbide only, or tungsten carbide head on a steel shank), potentially affecting their vibration. Although they found differences between the bur types, no significant differences were seen *within* each type, but discrepancies in alignment of cutting heads resulted in a range of concentricity errors up to 71 µm. Sample sizes were limited to only five burs of each type, and it would be interesting to compare more. Their study focused on the tooth-cutting interactions of bladed tungsten carbide burs, whereas the vibrations in this final part of the current investigation were recorded whilst cutting with diamond-coated instruments. It is proposed that the quality of construction of the diamond RCIs may have influenced the vibrations measured at the turbine head. Another possibility is that the instruments had not been inserted into the chuck to the same extent; this could be clarified with further testing.

## 8.6 Future directions

The potential for further investigation of discrepancies in instrument rotation rates has been discussed in section 8.1. Vibration frequencies were used to calculate these rotation rates whilst the instruments were unloaded. These rates are limited by the frictional forces operating within the handpiece[163]. It would also be possible to derive the rotation rates of the instruments whilst cutting. The instrument would be expected to rotate more slowly than when unloaded, due to an increase in resistance as the RCI contacts the tooth[163].

One potential criticism of the current research was that only one handpiece of each type was used, due to financial limitations. There may be discrepancies between handpieces of the same type, which would only become apparent with a larger sample size. Dyson[191] found considerable inconsistencies in performance characteristics (including vibration) within each of the two types of disposable handpieces examined. In general, however, he believes that other (ie non-disposable) handpieces can be assumed to be consistent in their engineering and performance (Dyson JE 2006, personal communication, March 31), so it is hoped that the results included within this report are representative of the models used. Nevertheless, it would be preferable to test a higher number of handpieces and models.

The vibrations measured in this research were those that occurred in one plane, ie towards and away from the scanning head. It is likely that other vibrations were also occurring in vertical and lateral planes, but these would have remained undetected by this equipment. A 3D (or triaxis) scanning laser vibrometer[192] could be used to investigate the movements in all directions, to provide a more complete description of handpiece vibration patterns. It may be possible in future to use a rotational laser vibrometer to characterise the movement of the RCIs, but at present they are limited to investigations of objects rotating at speeds up to 20 krpm[193].

An observation made in this study is that there are inconsistencies within the cutting instruments even when previously unused, which is in agreement with other researchers[19]. Tool imbalance may be associated with vibration[191]. In the dental clinic, instruments can become bent (or broken), and it is hypothesised that the subsequent eccentric rotation would have a substantial influence on the vibration of handpieces. It would be interesting to pursue this and perform further research into the relationship between eccentric instrument rotation and handpiece vibration.

During the course of these investigations, it was noted that vibrations in the teeth under load appeared to differ depending on the hardness of the tissue being cut. This is consistent with the observation of Henry and Peyton[11] that the harmonic content of the vibration becomes higher with increasing hardness. It is possible to use laser vibrometry to measure the differences in vibration frequency or magnitude of the teeth due to defects such as caries[194]. Dentine is softened when caries causes demineralisation[26], and the vibration pattern differs from that of healthy dentine.

It is proposed that a selective cutting tool could be developed to remove only necrotic dentine whilst preserving sound tissue – a criterion that has been mentioned as a requirement for an ideal cutting instrument[76]. A similar principle was recently suggested by Vila Verde[107], whereby characteristic sound signatures of laser ablation are used to indicate when tissue removal should cease. Process monitoring and control systems are already being exploited in industrial manufacturing, using sensors to detect acoustic emissions or relative vibrations between cutting tools (drills) and workpieces, to estimate surface roughness or predict tool wear/breakage[82]. If handpieces could be adapted to utilise a feedback mechanism to alter the rate of cutting in response to changing dentine hardness (detected by vibration characteristics), over-extension of cavity margins might be more easily avoided.

# CHAPTER 9

# CONCLUSIONS

- Measured maximum instrument rotation rates were similar to those documented in handpiece manufacturers' literature.
- It was confirmed that it is possible to use a SLV to measure vibration displacement amplitudes of high-speed dental handpieces.
- Unloaded vibration displacement amplitudes of turbines and speed-increasing handpieces were variable, yet remained under 4 μm in magnitude.
- Vibrations of unloaded handpieces were greater when equipped with a RCI than when the chuck remained vacant.
- More vibration activity was recorded at the head end of unloaded handpieces than further along the body.
- Under loaded conditions, the overall effect of handpiece type resulted in no significant differences in vibration displacement amplitudes, although further statistical scrutiny revealed differences when the interactions of other variables were considered.
- Significant differences were found between two types of cutting instrument (diamond and tungsten carbide) during vibration recordings of loaded handpieces, but the direction of the effect (ie an increase or decrease) was dependent on the handpiece model.
- Vibration amplitudes of handpiece heads increased significantly when loading of the instrument increased from 100 to 150 g.
- Significant inconsistencies were found within a sample of cutting instruments of the same type, with regard to the vibrations recorded in the handpiece head whilst cutting.

- There were no significant differences between mean vibrations of handpieces when cutting into ten different extracted teeth.

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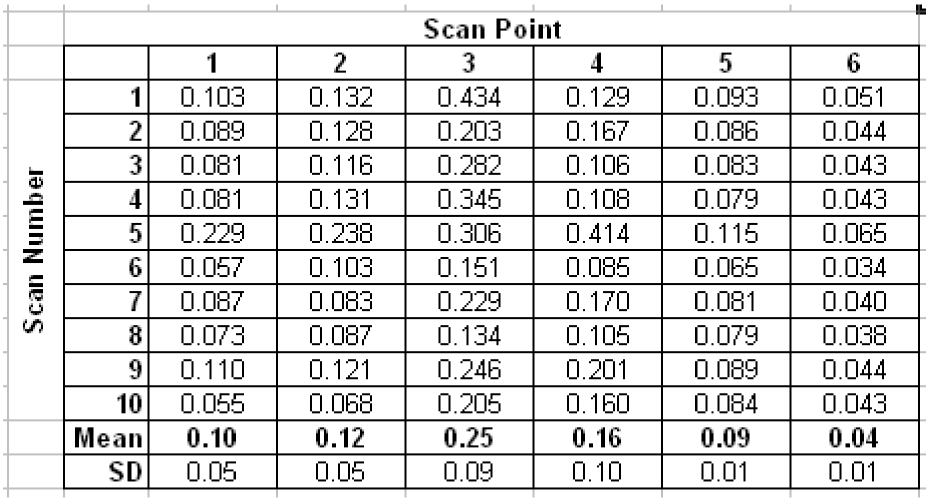
# APPENDIX

## 11.1 Raw data

### 11.1.1 Unloaded data

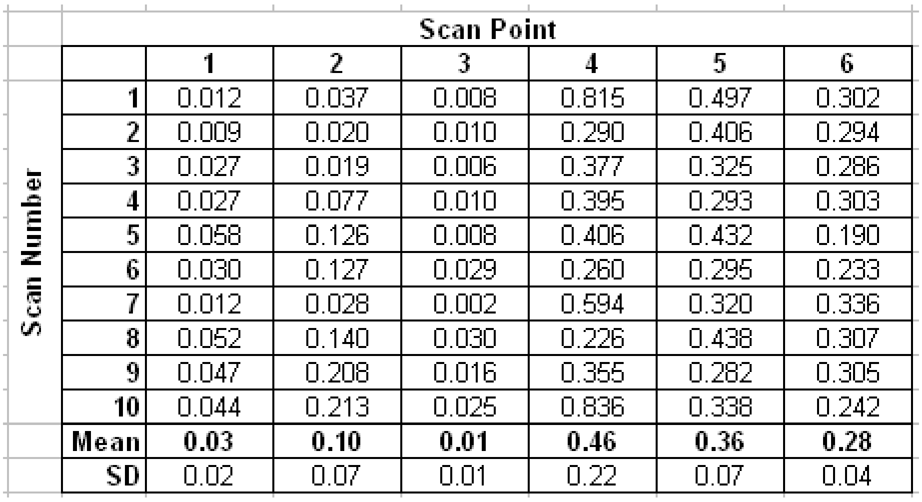
Contents of the following tables refer to vibration displacement amplitudes in μm.

**WA99A with RCI**



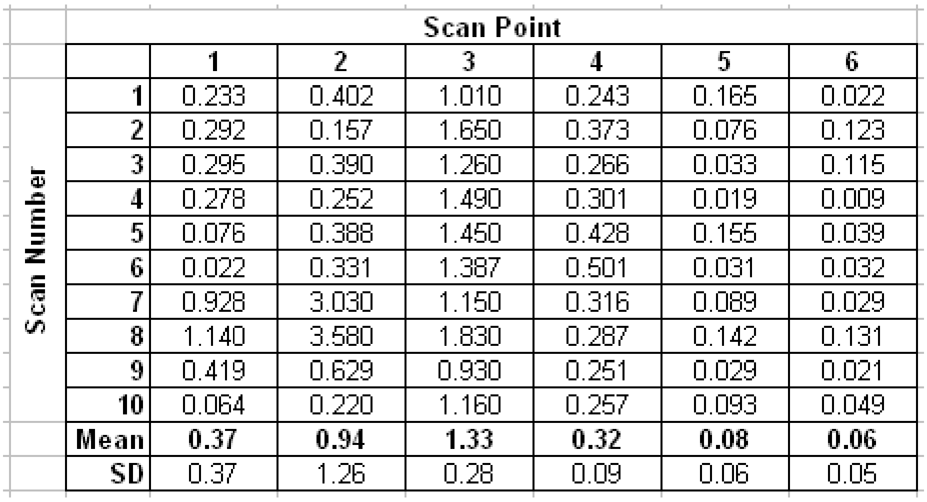
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.103 | 0.132 | 0.434 | 0.129 | 0.093 | 0.051 |
| | 2 | 0.089 | 0.128 | 0.203 | 0.167 | 0.086 | 0.044 |
| | 3 | 0.081 | 0.116 | 0.282 | 0.106 | 0.083 | 0.043 |
| | 4 | 0.081 | 0.131 | 0.345 | 0.108 | 0.079 | 0.043 |
| | 5 | 0.229 | 0.238 | 0.306 | 0.414 | 0.115 | 0.065 |
| | 6 | 0.057 | 0.103 | 0.151 | 0.085 | 0.065 | 0.034 |
| | 7 | 0.087 | 0.083 | 0.229 | 0.170 | 0.081 | 0.040 |
| | 8 | 0.073 | 0.087 | 0.134 | 0.105 | 0.079 | 0.038 |
| | 9 | 0.110 | 0.121 | 0.246 | 0.201 | 0.089 | 0.044 |
| | 10 | 0.055 | 0.068 | 0.205 | 0.160 | 0.084 | 0.043 |
| | **Mean** | **0.10** | **0.12** | **0.25** | **0.16** | **0.09** | **0.04** |
| | **SD** | 0.05 | 0.05 | 0.09 | 0.10 | 0.01 | 0.01 |

**WA99A without RCI**



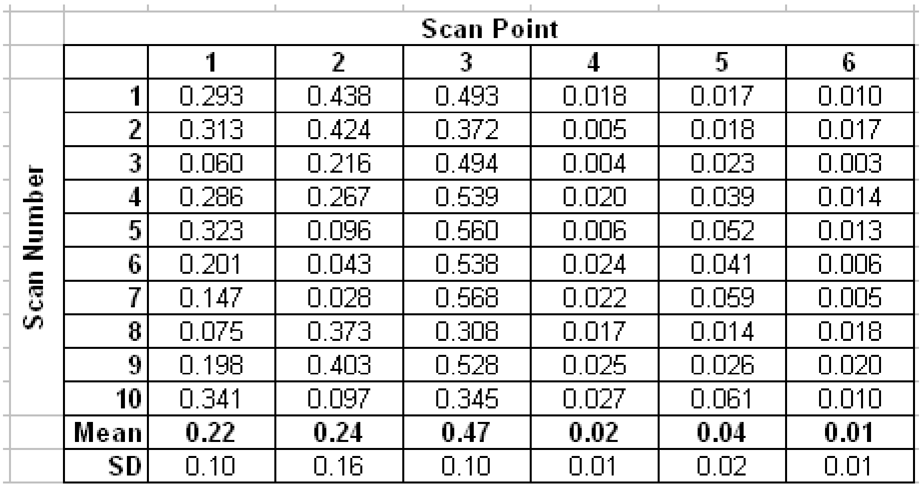
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.012 | 0.037 | 0.008 | 0.815 | 0.497 | 0.302 |
| | 2 | 0.009 | 0.020 | 0.010 | 0.290 | 0.406 | 0.294 |
| | 3 | 0.027 | 0.019 | 0.006 | 0.377 | 0.325 | 0.286 |
| | 4 | 0.027 | 0.077 | 0.010 | 0.395 | 0.293 | 0.303 |
| | 5 | 0.058 | 0.126 | 0.008 | 0.406 | 0.432 | 0.190 |
| | 6 | 0.030 | 0.127 | 0.029 | 0.260 | 0.295 | 0.233 |
| | 7 | 0.012 | 0.028 | 0.002 | 0.594 | 0.320 | 0.336 |
| | 8 | 0.052 | 0.140 | 0.030 | 0.226 | 0.438 | 0.307 |
| | 9 | 0.047 | 0.208 | 0.016 | 0.355 | 0.282 | 0.305 |
| | 10 | 0.044 | 0.213 | 0.025 | 0.836 | 0.338 | 0.242 |
| | **Mean** | **0.03** | **0.10** | **0.01** | **0.46** | **0.36** | **0.28** |
| | **SD** | 0.02 | 0.07 | 0.01 | 0.22 | 0.07 | 0.04 |

## 25CHC with RCI



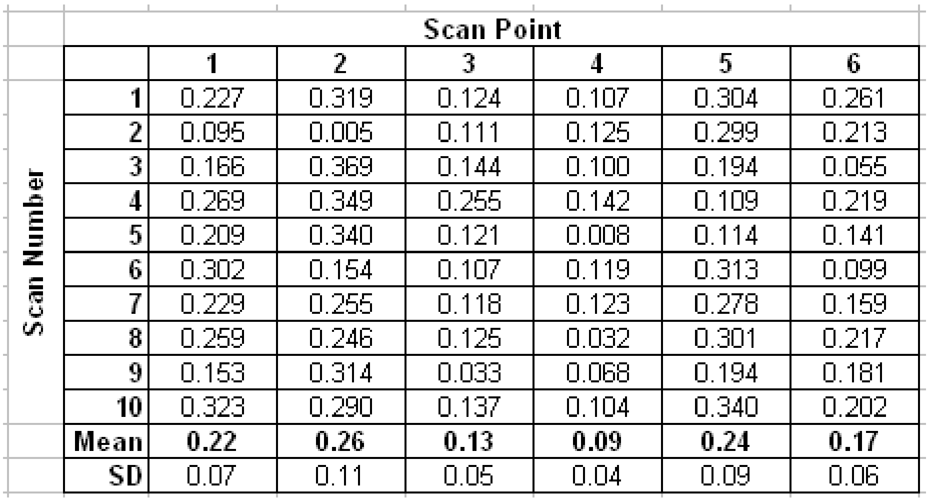
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.233 | 0.402 | 1.010 | 0.243 | 0.165 | 0.022 |
| | 2 | 0.292 | 0.157 | 1.650 | 0.373 | 0.076 | 0.123 |
| | 3 | 0.295 | 0.390 | 1.260 | 0.266 | 0.033 | 0.115 |
| | 4 | 0.278 | 0.252 | 1.490 | 0.301 | 0.019 | 0.009 |
| | 5 | 0.076 | 0.388 | 1.450 | 0.428 | 0.155 | 0.039 |
| | 6 | 0.022 | 0.331 | 1.387 | 0.501 | 0.031 | 0.032 |
| | 7 | 0.928 | 3.030 | 1.150 | 0.316 | 0.089 | 0.029 |
| | 8 | 1.140 | 3.580 | 1.830 | 0.287 | 0.142 | 0.131 |
| | 9 | 0.419 | 0.629 | 0.930 | 0.251 | 0.029 | 0.021 |
| | 10 | 0.064 | 0.220 | 1.160 | 0.257 | 0.093 | 0.049 |
| | **Mean** | **0.37** | **0.94** | **1.33** | **0.32** | **0.08** | **0.06** |
| | **SD** | 0.37 | 1.26 | 0.28 | 0.09 | 0.06 | 0.05 |

## 25CHC without RCI



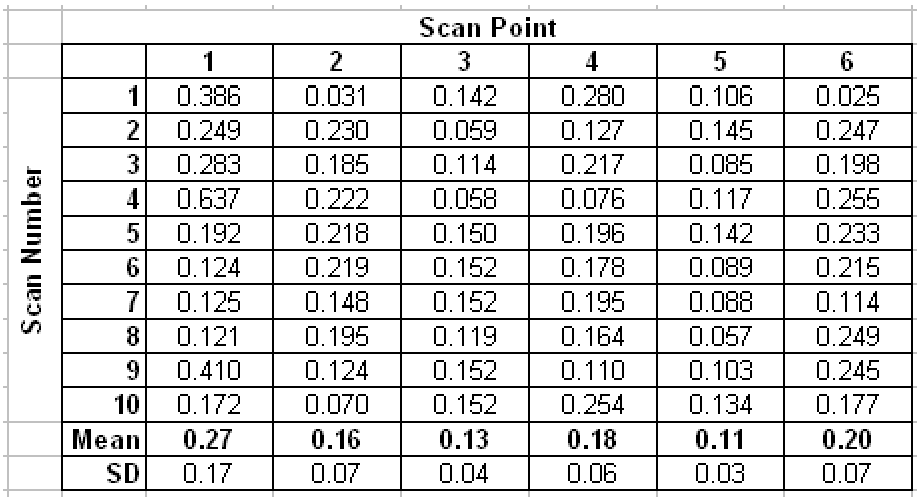
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.293 | 0.438 | 0.493 | 0.018 | 0.017 | 0.010 |
| | 2 | 0.313 | 0.424 | 0.372 | 0.005 | 0.018 | 0.017 |
| | 3 | 0.060 | 0.216 | 0.494 | 0.004 | 0.023 | 0.003 |
| | 4 | 0.286 | 0.267 | 0.539 | 0.020 | 0.039 | 0.014 |
| | 5 | 0.323 | 0.096 | 0.560 | 0.006 | 0.052 | 0.013 |
| | 6 | 0.201 | 0.043 | 0.538 | 0.024 | 0.041 | 0.006 |
| | 7 | 0.147 | 0.028 | 0.568 | 0.022 | 0.059 | 0.005 |
| | 8 | 0.075 | 0.373 | 0.308 | 0.017 | 0.014 | 0.018 |
| | 9 | 0.198 | 0.403 | 0.528 | 0.025 | 0.026 | 0.020 |
| | 10 | 0.341 | 0.097 | 0.345 | 0.027 | 0.061 | 0.010 |
| | **Mean** | **0.22** | **0.24** | **0.47** | **0.02** | **0.04** | **0.01** |
| | **SD** | 0.10 | 0.16 | 0.10 | 0.01 | 0.02 | 0.01 |

## TA98CM with RCI



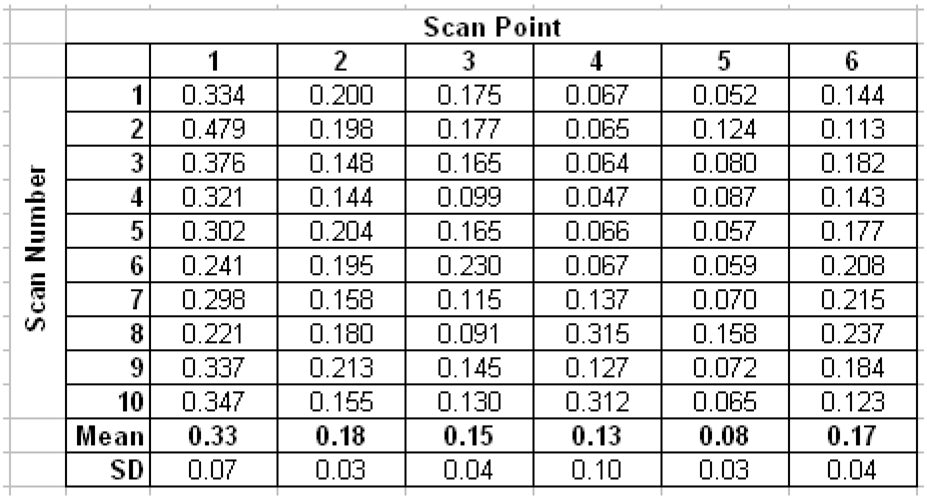
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.227 | 0.319 | 0.124 | 0.107 | 0.304 | 0.261 |
| | 2 | 0.095 | 0.005 | 0.111 | 0.125 | 0.299 | 0.213 |
| | 3 | 0.166 | 0.369 | 0.144 | 0.100 | 0.194 | 0.055 |
| | 4 | 0.269 | 0.349 | 0.255 | 0.142 | 0.109 | 0.219 |
| | 5 | 0.209 | 0.340 | 0.121 | 0.008 | 0.114 | 0.141 |
| | 6 | 0.302 | 0.154 | 0.107 | 0.119 | 0.313 | 0.099 |
| | 7 | 0.229 | 0.255 | 0.118 | 0.123 | 0.278 | 0.159 |
| | 8 | 0.259 | 0.246 | 0.125 | 0.032 | 0.301 | 0.217 |
| | 9 | 0.153 | 0.314 | 0.033 | 0.068 | 0.194 | 0.181 |
| | 10 | 0.323 | 0.290 | 0.137 | 0.104 | 0.340 | 0.202 |
| | **Mean** | **0.22** | **0.26** | **0.13** | **0.09** | **0.24** | **0.17** |
| | **SD** | 0.07 | 0.11 | 0.05 | 0.04 | 0.09 | 0.06 |

## TA98CM without RCI



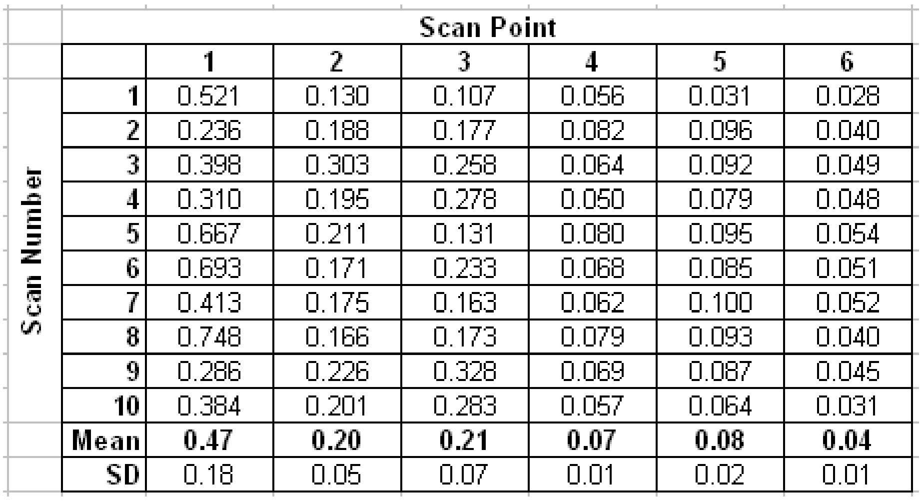
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.386 | 0.031 | 0.142 | 0.280 | 0.106 | 0.025 |
| | 2 | 0.249 | 0.230 | 0.059 | 0.127 | 0.145 | 0.247 |
| | 3 | 0.283 | 0.185 | 0.114 | 0.217 | 0.085 | 0.198 |
| | 4 | 0.637 | 0.222 | 0.058 | 0.076 | 0.117 | 0.255 |
| | 5 | 0.192 | 0.218 | 0.150 | 0.196 | 0.142 | 0.233 |
| | 6 | 0.124 | 0.219 | 0.152 | 0.178 | 0.089 | 0.215 |
| | 7 | 0.125 | 0.148 | 0.152 | 0.195 | 0.088 | 0.114 |
| | 8 | 0.121 | 0.195 | 0.119 | 0.164 | 0.057 | 0.249 |
| | 9 | 0.410 | 0.124 | 0.152 | 0.110 | 0.103 | 0.245 |
| | 10 | 0.172 | 0.070 | 0.152 | 0.254 | 0.134 | 0.177 |
| | **Mean** | **0.27** | **0.16** | **0.13** | **0.18** | **0.11** | **0.20** |
| | **SD** | 0.17 | 0.07 | 0.04 | 0.06 | 0.03 | 0.07 |

## 660C with RCI



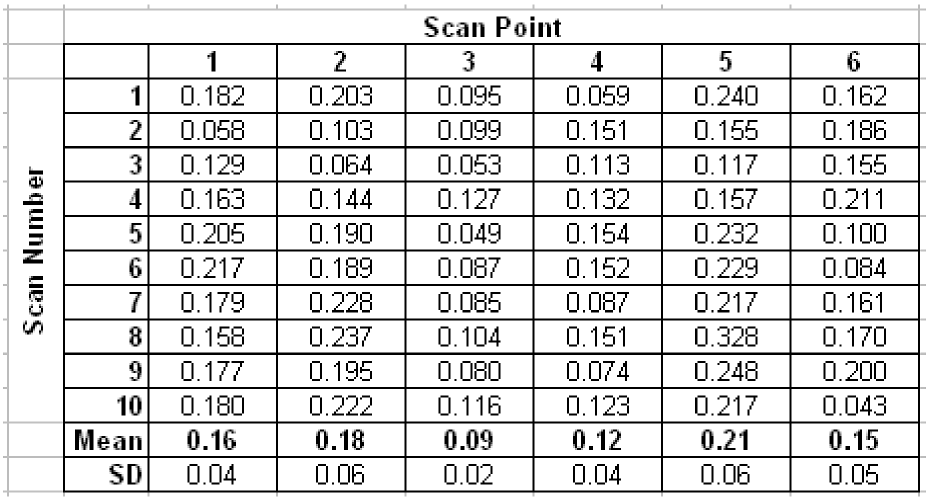
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.334 | 0.200 | 0.175 | 0.067 | 0.052 | 0.144 |
| | 2 | 0.479 | 0.198 | 0.177 | 0.065 | 0.124 | 0.113 |
| | 3 | 0.376 | 0.148 | 0.165 | 0.064 | 0.080 | 0.182 |
| | 4 | 0.321 | 0.144 | 0.099 | 0.047 | 0.087 | 0.143 |
| | 5 | 0.302 | 0.204 | 0.165 | 0.066 | 0.057 | 0.177 |
| | 6 | 0.241 | 0.195 | 0.230 | 0.067 | 0.059 | 0.208 |
| | 7 | 0.298 | 0.158 | 0.115 | 0.137 | 0.070 | 0.215 |
| | 8 | 0.221 | 0.180 | 0.091 | 0.315 | 0.158 | 0.237 |
| | 9 | 0.337 | 0.213 | 0.145 | 0.127 | 0.072 | 0.184 |
| | 10 | 0.347 | 0.155 | 0.130 | 0.312 | 0.065 | 0.123 |
| | **Mean** | **0.33** | **0.18** | **0.15** | **0.13** | **0.08** | **0.17** |
| | **SD** | 0.07 | 0.03 | 0.04 | 0.10 | 0.03 | 0.04 |

## 660C without RCI



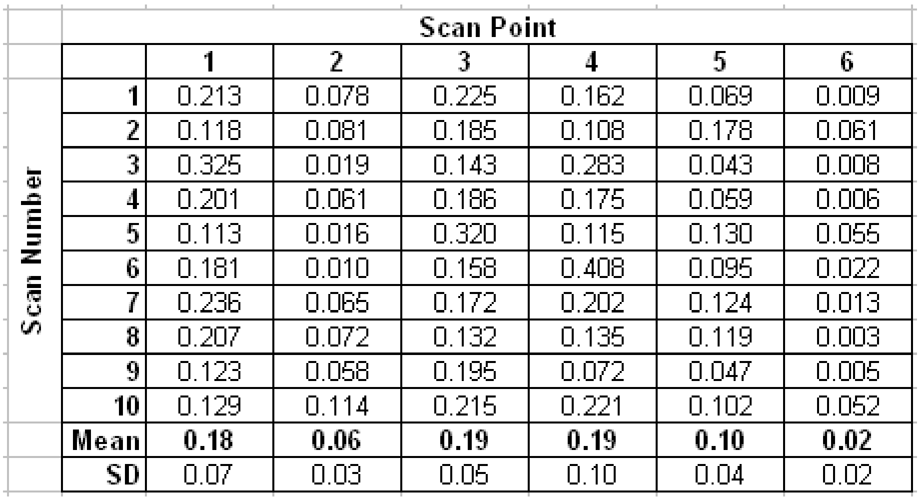
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.521 | 0.130 | 0.107 | 0.056 | 0.031 | 0.028 |
| | 2 | 0.236 | 0.188 | 0.177 | 0.082 | 0.096 | 0.040 |
| | 3 | 0.398 | 0.303 | 0.258 | 0.064 | 0.092 | 0.049 |
| | 4 | 0.310 | 0.195 | 0.278 | 0.050 | 0.079 | 0.048 |
| | 5 | 0.667 | 0.211 | 0.131 | 0.080 | 0.095 | 0.054 |
| | 6 | 0.693 | 0.171 | 0.233 | 0.068 | 0.085 | 0.051 |
| | 7 | 0.413 | 0.175 | 0.163 | 0.062 | 0.100 | 0.052 |
| | 8 | 0.748 | 0.166 | 0.173 | 0.079 | 0.093 | 0.040 |
| | 9 | 0.286 | 0.226 | 0.328 | 0.069 | 0.087 | 0.045 |
| | 10 | 0.384 | 0.201 | 0.283 | 0.057 | 0.064 | 0.031 |
| | **Mean** | **0.47** | **0.20** | **0.21** | **0.07** | **0.08** | **0.04** |
| | **SD** | 0.18 | 0.05 | 0.07 | 0.01 | 0.02 | 0.01 |

## TA96CM with RCI



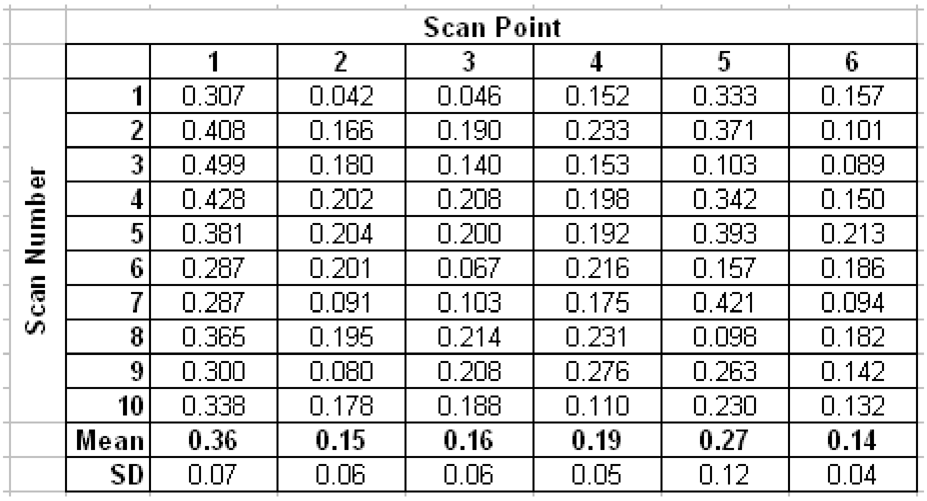
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.182 | 0.203 | 0.095 | 0.059 | 0.240 | 0.162 |
| | 2 | 0.058 | 0.103 | 0.099 | 0.151 | 0.155 | 0.186 |
| | 3 | 0.129 | 0.064 | 0.053 | 0.113 | 0.117 | 0.155 |
| | 4 | 0.163 | 0.144 | 0.127 | 0.132 | 0.157 | 0.211 |
| | 5 | 0.205 | 0.190 | 0.049 | 0.154 | 0.232 | 0.100 |
| | 6 | 0.217 | 0.189 | 0.087 | 0.152 | 0.229 | 0.084 |
| | 7 | 0.179 | 0.228 | 0.085 | 0.087 | 0.217 | 0.161 |
| | 8 | 0.158 | 0.237 | 0.104 | 0.151 | 0.328 | 0.170 |
| | 9 | 0.177 | 0.195 | 0.080 | 0.074 | 0.248 | 0.200 |
| | 10 | 0.180 | 0.222 | 0.116 | 0.123 | 0.217 | 0.043 |
| | **Mean** | **0.16** | **0.18** | **0.09** | **0.12** | **0.21** | **0.15** |
| | **SD** | 0.04 | 0.06 | 0.02 | 0.04 | 0.06 | 0.05 |

## TA96CM without RCI



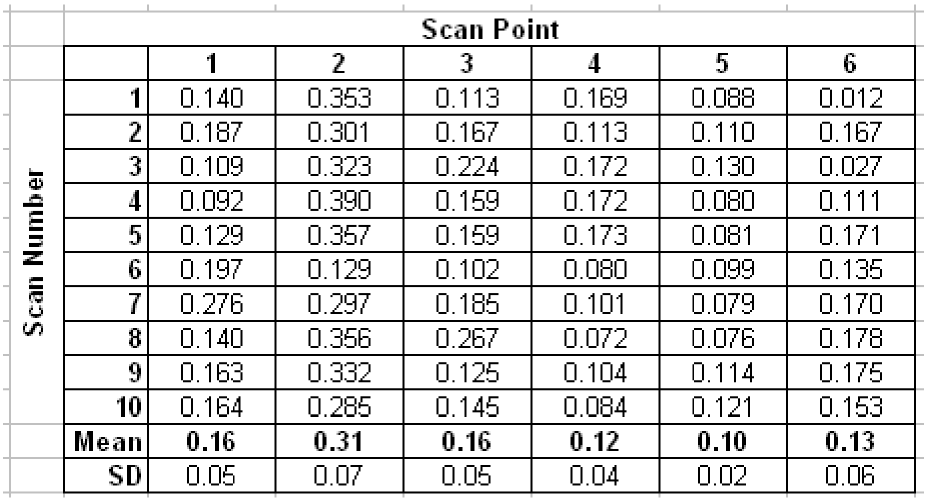
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.213 | 0.078 | 0.225 | 0.162 | 0.069 | 0.009 |
| | 2 | 0.118 | 0.081 | 0.185 | 0.108 | 0.178 | 0.061 |
| | 3 | 0.325 | 0.019 | 0.143 | 0.283 | 0.043 | 0.008 |
| | 4 | 0.201 | 0.061 | 0.186 | 0.175 | 0.059 | 0.006 |
| | 5 | 0.113 | 0.016 | 0.320 | 0.115 | 0.130 | 0.055 |
| | 6 | 0.181 | 0.010 | 0.158 | 0.408 | 0.095 | 0.022 |
| | 7 | 0.236 | 0.065 | 0.172 | 0.202 | 0.124 | 0.013 |
| | 8 | 0.207 | 0.072 | 0.132 | 0.135 | 0.119 | 0.003 |
| | 9 | 0.123 | 0.058 | 0.195 | 0.072 | 0.047 | 0.005 |
| | 10 | 0.129 | 0.114 | 0.215 | 0.221 | 0.102 | 0.052 |
| | **Mean** | **0.18** | **0.06** | **0.19** | **0.19** | **0.10** | **0.02** |
| | **SD** | 0.07 | 0.03 | 0.05 | 0.10 | 0.04 | 0.02 |

**637C with RCI**



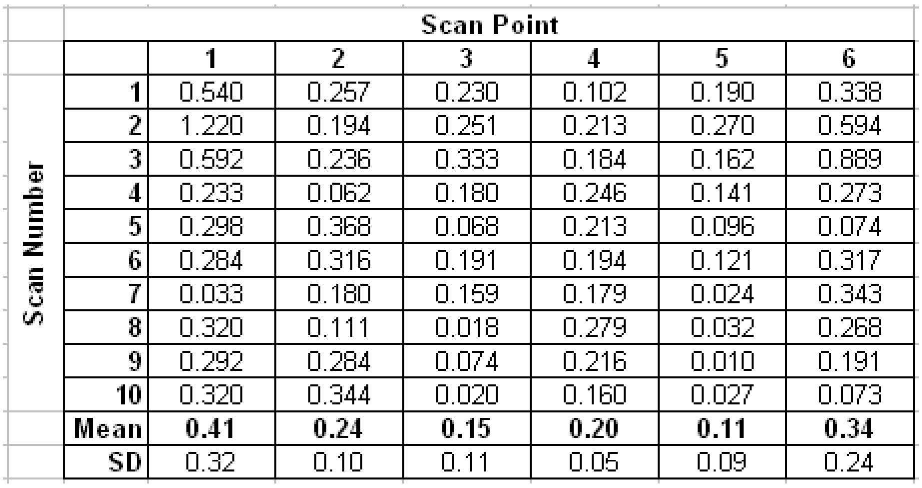
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.307 | 0.042 | 0.046 | 0.152 | 0.333 | 0.157 |
| | 2 | 0.408 | 0.166 | 0.190 | 0.233 | 0.371 | 0.101 |
| | 3 | 0.499 | 0.180 | 0.140 | 0.153 | 0.103 | 0.089 |
| | 4 | 0.428 | 0.202 | 0.208 | 0.198 | 0.342 | 0.150 |
| | 5 | 0.381 | 0.204 | 0.200 | 0.192 | 0.393 | 0.213 |
| | 6 | 0.287 | 0.201 | 0.067 | 0.216 | 0.157 | 0.186 |
| | 7 | 0.287 | 0.091 | 0.103 | 0.175 | 0.421 | 0.094 |
| | 8 | 0.365 | 0.195 | 0.214 | 0.231 | 0.098 | 0.182 |
| | 9 | 0.300 | 0.080 | 0.208 | 0.276 | 0.263 | 0.142 |
| | 10 | 0.338 | 0.178 | 0.188 | 0.110 | 0.230 | 0.132 |
| | **Mean** | **0.36** | **0.15** | **0.16** | **0.19** | **0.27** | **0.14** |
| | **SD** | 0.07 | 0.06 | 0.06 | 0.05 | 0.12 | 0.04 |

**636C without RCI**



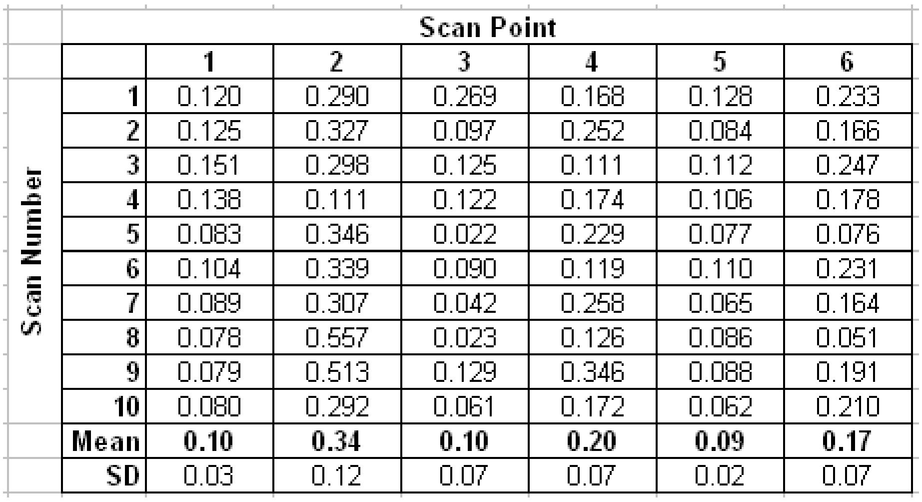
| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.140 | 0.353 | 0.113 | 0.169 | 0.088 | 0.012 |
| | 2 | 0.187 | 0.301 | 0.167 | 0.113 | 0.110 | 0.167 |
| | 3 | 0.109 | 0.323 | 0.224 | 0.172 | 0.130 | 0.027 |
| | 4 | 0.092 | 0.390 | 0.159 | 0.172 | 0.080 | 0.111 |
| | 5 | 0.129 | 0.357 | 0.159 | 0.173 | 0.081 | 0.171 |
| | 6 | 0.197 | 0.129 | 0.102 | 0.080 | 0.099 | 0.135 |
| | 7 | 0.276 | 0.297 | 0.185 | 0.101 | 0.079 | 0.170 |
| | 8 | 0.140 | 0.356 | 0.267 | 0.072 | 0.076 | 0.178 |
| | 9 | 0.163 | 0.332 | 0.125 | 0.104 | 0.114 | 0.175 |
| | 10 | 0.164 | 0.285 | 0.145 | 0.084 | 0.121 | 0.153 |
| | **Mean** | **0.16** | **0.31** | **0.16** | **0.12** | **0.10** | **0.13** |
| | **SD** | 0.05 | 0.07 | 0.05 | 0.04 | 0.02 | 0.06 |

**TA98M with RCI**



| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.540 | 0.257 | 0.230 | 0.102 | 0.190 | 0.338 |
| | 2 | 1.220 | 0.194 | 0.251 | 0.213 | 0.270 | 0.594 |
| | 3 | 0.592 | 0.236 | 0.333 | 0.184 | 0.162 | 0.889 |
| | 4 | 0.233 | 0.062 | 0.180 | 0.246 | 0.141 | 0.273 |
| | 5 | 0.298 | 0.368 | 0.068 | 0.213 | 0.096 | 0.074 |
| | 6 | 0.284 | 0.316 | 0.191 | 0.194 | 0.121 | 0.317 |
| | 7 | 0.033 | 0.180 | 0.159 | 0.179 | 0.024 | 0.343 |
| | 8 | 0.320 | 0.111 | 0.018 | 0.279 | 0.032 | 0.268 |
| | 9 | 0.292 | 0.284 | 0.074 | 0.216 | 0.010 | 0.191 |
| | 10 | 0.320 | 0.344 | 0.020 | 0.160 | 0.027 | 0.073 |
| | **Mean** | **0.41** | **0.24** | **0.15** | **0.20** | **0.11** | **0.34** |
| | **SD** | 0.32 | 0.10 | 0.11 | 0.05 | 0.09 | 0.24 |

**TA98M without RCI**

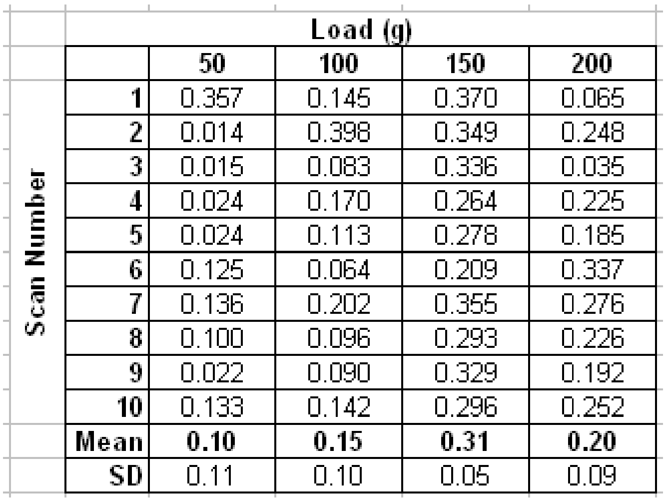


| | | Scan Point | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| Scan Number | 1 | 0.120 | 0.290 | 0.269 | 0.168 | 0.128 | 0.233 |
| | 2 | 0.125 | 0.327 | 0.097 | 0.252 | 0.084 | 0.166 |
| | 3 | 0.151 | 0.298 | 0.125 | 0.111 | 0.112 | 0.247 |
| | 4 | 0.138 | 0.111 | 0.122 | 0.174 | 0.106 | 0.178 |
| | 5 | 0.083 | 0.346 | 0.022 | 0.229 | 0.077 | 0.076 |
| | 6 | 0.104 | 0.339 | 0.090 | 0.119 | 0.110 | 0.231 |
| | 7 | 0.089 | 0.307 | 0.042 | 0.258 | 0.065 | 0.164 |
| | 8 | 0.078 | 0.557 | 0.023 | 0.126 | 0.086 | 0.051 |
| | 9 | 0.079 | 0.513 | 0.129 | 0.346 | 0.088 | 0.191 |
| | 10 | 0.080 | 0.292 | 0.061 | 0.172 | 0.062 | 0.210 |
| | **Mean** | **0.10** | **0.34** | **0.10** | **0.20** | **0.09** | **0.17** |
| | **SD** | 0.03 | 0.12 | 0.07 | 0.07 | 0.02 | 0.07 |

### 11.1.2 Loaded data

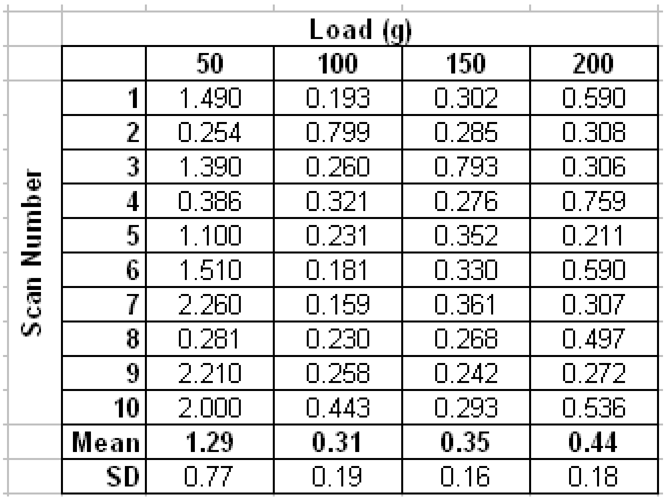
Contents of the following tables refer to vibration displacement amplitudes in µm.

**TA98CM with diamond RCI**



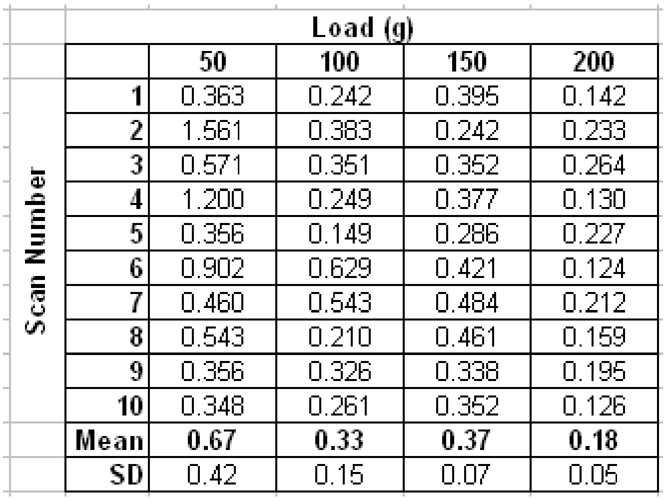
| | | Load (g) | | | |
|---|---|---|---|---|---|
| | | 50 | 100 | 150 | 200 |
| Scan Number | 1 | 0.357 | 0.145 | 0.370 | 0.065 |
| | 2 | 0.014 | 0.398 | 0.349 | 0.248 |
| | 3 | 0.015 | 0.083 | 0.336 | 0.035 |
| | 4 | 0.024 | 0.170 | 0.264 | 0.225 |
| | 5 | 0.024 | 0.113 | 0.278 | 0.185 |
| | 6 | 0.125 | 0.064 | 0.209 | 0.337 |
| | 7 | 0.136 | 0.202 | 0.355 | 0.276 |
| | 8 | 0.100 | 0.096 | 0.293 | 0.226 |
| | 9 | 0.022 | 0.090 | 0.329 | 0.192 |
| | 10 | 0.133 | 0.142 | 0.296 | 0.252 |
| | **Mean** | **0.10** | **0.15** | **0.31** | **0.20** |
| | **SD** | 0.11 | 0.10 | 0.05 | 0.09 |

**TA98CM with tungsten carbide RCI**



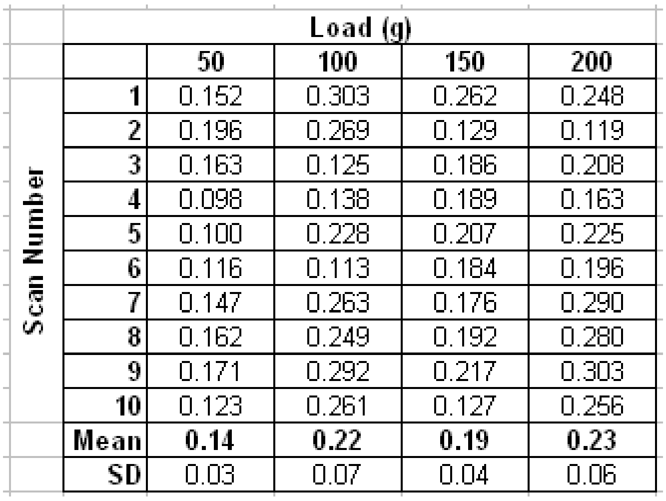
| | | Load (g) | | | |
|---|---|---|---|---|---|
| | | 50 | 100 | 150 | 200 |
| Scan Number | 1 | 1.490 | 0.193 | 0.302 | 0.590 |
| | 2 | 0.254 | 0.799 | 0.285 | 0.308 |
| | 3 | 1.390 | 0.260 | 0.793 | 0.306 |
| | 4 | 0.386 | 0.321 | 0.276 | 0.759 |
| | 5 | 1.100 | 0.231 | 0.352 | 0.211 |
| | 6 | 1.510 | 0.181 | 0.330 | 0.590 |
| | 7 | 2.260 | 0.159 | 0.361 | 0.307 |
| | 8 | 0.281 | 0.230 | 0.268 | 0.497 |
| | 9 | 2.210 | 0.258 | 0.242 | 0.272 |
| | 10 | 2.000 | 0.443 | 0.293 | 0.536 |
| | **Mean** | **1.29** | **0.31** | **0.35** | **0.44** |
| | **SD** | 0.77 | 0.19 | 0.16 | 0.18 |

## 660C with diamond RCI



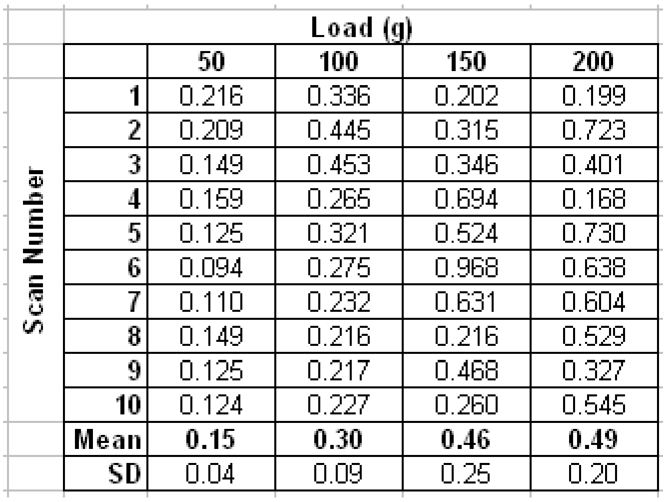
| | | Load (g) | | | |
|---|---|---|---|---|---|
| | | 50 | 100 | 150 | 200 |
| Scan Number | 1 | 0.363 | 0.242 | 0.395 | 0.142 |
| | 2 | 1.561 | 0.383 | 0.242 | 0.233 |
| | 3 | 0.571 | 0.351 | 0.352 | 0.264 |
| | 4 | 1.200 | 0.249 | 0.377 | 0.130 |
| | 5 | 0.356 | 0.149 | 0.286 | 0.227 |
| | 6 | 0.902 | 0.629 | 0.421 | 0.124 |
| | 7 | 0.460 | 0.543 | 0.484 | 0.212 |
| | 8 | 0.543 | 0.210 | 0.461 | 0.159 |
| | 9 | 0.356 | 0.326 | 0.338 | 0.195 |
| | 10 | 0.348 | 0.261 | 0.352 | 0.126 |
| | **Mean** | **0.67** | **0.33** | **0.37** | **0.18** |
| | **SD** | 0.42 | 0.15 | 0.07 | 0.05 |

## 660C with tungsten carbide RCI



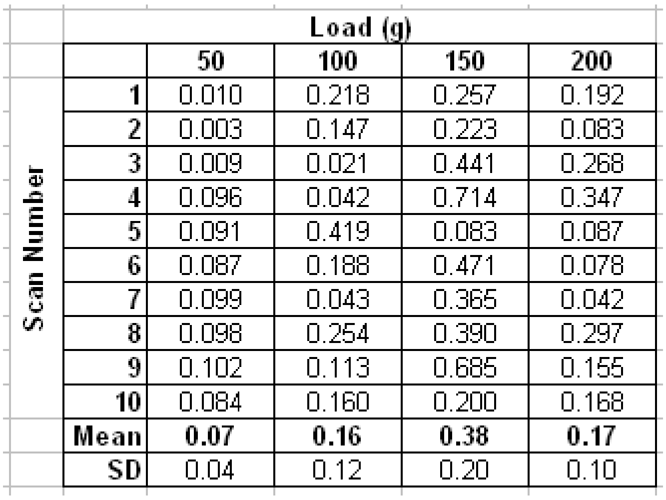
| | | Load (g) | | | |
|---|---|---|---|---|---|
| | | 50 | 100 | 150 | 200 |
| Scan Number | 1 | 0.152 | 0.303 | 0.262 | 0.248 |
| | 2 | 0.196 | 0.269 | 0.129 | 0.119 |
| | 3 | 0.163 | 0.125 | 0.186 | 0.208 |
| | 4 | 0.098 | 0.138 | 0.189 | 0.163 |
| | 5 | 0.100 | 0.228 | 0.207 | 0.225 |
| | 6 | 0.116 | 0.113 | 0.184 | 0.196 |
| | 7 | 0.147 | 0.263 | 0.176 | 0.290 |
| | 8 | 0.162 | 0.249 | 0.192 | 0.280 |
| | 9 | 0.171 | 0.292 | 0.217 | 0.303 |
| | 10 | 0.123 | 0.261 | 0.127 | 0.256 |
| | **Mean** | **0.14** | **0.22** | **0.19** | **0.23** |
| | **SD** | 0.03 | 0.07 | 0.04 | 0.06 |

## TA96CM with diamond RCI



| | | Load (g) | | | |
|---|---|---|---|---|---|
| | | 50 | 100 | 150 | 200 |
| Scan Number | 1 | 0.216 | 0.336 | 0.202 | 0.199 |
| | 2 | 0.209 | 0.445 | 0.315 | 0.723 |
| | 3 | 0.149 | 0.453 | 0.346 | 0.401 |
| | 4 | 0.159 | 0.265 | 0.694 | 0.168 |
| | 5 | 0.125 | 0.321 | 0.524 | 0.730 |
| | 6 | 0.094 | 0.275 | 0.968 | 0.638 |
| | 7 | 0.110 | 0.232 | 0.631 | 0.604 |
| | 8 | 0.149 | 0.216 | 0.216 | 0.529 |
| | 9 | 0.125 | 0.217 | 0.468 | 0.327 |
| | 10 | 0.124 | 0.227 | 0.260 | 0.545 |
| | **Mean** | **0.15** | **0.30** | **0.46** | **0.49** |
| | **SD** | 0.04 | 0.09 | 0.25 | 0.20 |

## TA96CM with tungsten carbide RCI



| | | Load (g) | | | |
|---|---|---|---|---|---|
| | | 50 | 100 | 150 | 200 |
| Scan Number | 1 | 0.010 | 0.218 | 0.257 | 0.192 |
| | 2 | 0.003 | 0.147 | 0.223 | 0.083 |
| | 3 | 0.009 | 0.021 | 0.441 | 0.268 |
| | 4 | 0.096 | 0.042 | 0.714 | 0.347 |
| | 5 | 0.091 | 0.419 | 0.083 | 0.087 |
| | 6 | 0.087 | 0.188 | 0.471 | 0.078 |
| | 7 | 0.099 | 0.043 | 0.365 | 0.042 |
| | 8 | 0.098 | 0.254 | 0.390 | 0.297 |
| | 9 | 0.102 | 0.113 | 0.685 | 0.155 |
| | 10 | 0.084 | 0.160 | 0.200 | 0.168 |
| | **Mean** | **0.07** | **0.16** | **0.38** | **0.17** |
| | **SD** | 0.04 | 0.12 | 0.20 | 0.10 |

## 11.2 Conference abstracts

### 11.2.1 British Society for Dental Research (BSDR)

Durham, April 2007

### Vibrations of High-Speed Dental Handpieces Measured Using Laser Vibrometry

R.L. POOLE*, S.C. LEA, A.C.C. SHORTALL and A.D. WALMSLEY

School of Dentistry, The University of Birmingham, St. Chad's Queensway,
Birmingham, B4 6NN, UK.

Dental handpieces are used in dentistry to remove tooth substance as part of caries treatment. Handpiece oscillations have previously been measured using accelerometers and single-point laser vibrometry, showing limited representations of their vibratory patterns.

**Objectives**: To measure *in vitro* vibration displacement amplitudes of high-speed dental turbines and speed-increasing handpieces using a Scanning Laser Vibrometer (SLV).

**Methods**: Five turbines (KaVo 660C and 637C; W&H TA-98CM, TA-96CM and TA98M) and two speed-increasing handpieces (KaVo 25CHC and W&H WA-99A) were investigated using a Polytec SLV (PSV-300). Handpieces were operated with either no bur or a new, unused diamond fissure bur (Ash HiDi 541). Drive air pressures fell within the ranges recommended by the manufacturers. Frequency bands selected for analysis were consistent with expected rates of bur rotation, whilst the unloaded handpieces were operated at maximum speeds. Repeated measurements were made at six selected points on the handpiece, three at the head and three along the body. Results were investigated using analysis of variance (ANOVA).

**Results**: Mean values ranged from 0.01 (± 0.01) to 1.33 (± 0.28) µm. There were significant differences between handpiece models ($p < 0.05$). Within the results for each handpiece, variations in displacement amplitudes occurred between the areas targeted by the laser. The greatest activity was observed at the head end of the handpieces.

**Conclusions**: The SLV has shown that it is possible to visualise the vibratory patterns of high-speed dental handpieces. Variations in displacement amplitudes were observed under different conditions, although the magnitudes of the vibrations were small.

This work is supported by an EPSRC project grant (EP/D500834/1).

## 11.2.2 Pan European Federation (PEF IADR)

London, September 2008

### The Effect of Load on High-Speed Dental Handpiece Vibrations

R.L. POOLE*, S.C. LEA, A.C.C. SHORTALL and A.D. WALMSLEY

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Birmingham, B4 6NN, UK.

High-speed dental handpieces may potentially propagate cracks within tooth enamel as a result of the vibrations produced during the cutting process.

**Objectives**: To measure *in vitro* vibration displacement amplitudes of high-speed dental handpieces using a Scanning Laser Vibrometer (SLV), whilst cutting extracted teeth under various loads.

**Methods**: Extracted molar teeth were mounted on a laboratory pan-balance so that the tooth crown contacted the cutting instrument at a known load. A Polytec SLV (PSV-300) measured vibrations at the head and angle whilst handpieces were clamped in a fixed position. Repeated measurements were taken using a new diamond rotary cutting instrument (Ash HiDi 541) both unloaded and with increasing loads of 0.5 to 2.0 N. Drive air pressures fell within ranges recommended by the manufacturers. Handpieces were operated at maximum speeds with a coolant water spray. Results were investigated using analysis of variance (ANOVA).

**Results**: Vibration displacement amplitudes of handpieces were not significantly greater under loading compared to the unloaded situation ($p > 0.05$); increases in loading did not correspond with increases in displacement of the handpiece. Vibration activity at the head was greater than at the angle of the handpiece.

**Conclusion**: Contrary to expectations, increasing the loading of rotary cutting instruments did not result in increased vibration displacement amplitudes. However the data was consistent with our earlier work in that greater activity was found at the head, and the levels of vibration remained low (< 5 µm).

This work is supported by an EPSRC project grant (EP/D500834/1).

### 11.2.3 International Association for Dental Research (IADR)

Miami, April 2009

#### Evaluating Vibrations Transmitted Through Teeth During High-Speed Cutting

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School of Dentistry, The University of Birmingham, St. Chad's Queensway,
Birmingham, B4 6NN, UK.

Vibrations of high-speed dental handpieces are believed to have the potential to propagate cracks within tooth enamel during cavity preparation, thereby causing iatrogenic damage.

**Objectives**: To investigate the feasibility of using a scanning laser vibrometer to evaluate factors affecting the magnitude of vibrations transmitted through teeth.

**Methods**: A non-contact scanning laser vibrometer (Polytec PSV-300-F/S) was used to measure surface vibrations of extracted molars during cutting procedures. A high-speed dental turbine (KaVo TA98CM), equipped with a new diamond rotary cutting instrument (Ash Hi-Di 541), was used to cut into each tooth. The drive air pressure was 2.8 bar (40 psi) and water coolant was supplied at 50 ml/min. A tension/compression load cell (Sensotec Model 31) monitored the load applied to the tooth throughout the data collection period.

**Results**: A frequency peak was detected at around 5.4 kHz. The mean velocity of vibrations was 19.9 (±2.4) mm/s, whilst the average maximum vibration displacement amplitude was recorded at 0.59 (± 0.08) μm.

**Conclusion**: Vibrations are transmitted from the rotary cutting instrument through to the tooth surfaces. It is possible to measure the velocity and displacement amplitude of these vibrations using scanning laser vibrometry. Values recorded appeared to be affected by the force and direction of the instrument loading, and the type of dental tissue being cut. This preliminary study provides a basis for further research.

This work is supported by an EPSRC project grant (EP/D500834/1).

## 11.3 Publication

Poole RL, Lea SC, Dyson JE, Shortall ACC, Walmsley AD. Vibration characteristics of high-speed dental turbines and speed-increasing handpieces. *Journal of Dentistry* 2008;**36**:488-493.